

Proceedings of the International Conference on Innovation - driven Knowledge Economies and Transformation in the Global South



**Vol III - Knowledge- driven development of national , regional, local
and sectoral innovation systems and rural development**

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Volume III Knowledge- Driven Development of National , regional, local and sectoral innovation systems and rural development

11-14 OCTOBER 2023

Organized by

GLOBELICS | Gulati Institute of Finance and Taxation | Research and
Information System for Developing | Indian Institute of Management
Bangalore | Kerala Development and Innovation Strategic Council



Preface / A word of welcome and thanks

It is a matter of great pride that the 20th-anniversary Globelics International Conference is being held in Thiruvananthapuram. This conference deliberates on an issue of much contemporary relevance – Innovation-driven Knowledge Economies and Transformation in the Global South, which is at the centre stage of development strategy both at the national and that of the government of Kerala. In 2006, when inclusive development was a major issue of global concern, Globelics conference was held in Trivandrum and deliberated on Innovation Systems for International Competitiveness and Shared Prosperity.

This Conference intends to bring together scholars across disciplines from over 50 countries to pool together experiences and expertise to reflect on varied issues involved in the process of transforming developing economies into sustainable, resilient, and inclusive innovation-driven knowledge economies.

In the conference, to be inaugurated by Shri Pinaryi Vijayan, the Hon'ble Chief Minister of Kerala, scholars of eminence will join as keynote speakers and panelists in plenary sessions and special sessions. The conference, organized in nine parallel tracks, will also have book presentations, excursions, and cultural events. As part of the conference, about 20 leading scholars from Globelics will visit different universities and colleges in Kerala to deliver lectures and interact with faculty and students, which is facilitated by Kerala Higher Education Council and Kerala Economic Association.

We welcome with great appreciation the Honourable Chief Minister Shri Pinarayi Vijayan and all the dignitaries who joined us for the inaugural address and eminent scholars delivering keynotes and addressing in different plenary sessions, special sessions, and parallel sessions. While the invisible hand of our honourable Chief Minister is there in all the important initiatives of GIFT, this program has been ably guided and steered by our Chairperson Shri K N Balagopal, Hon'ble Finance Minister of Kerala.

This important event is the outcome of the collective effort of all those involved, especially the Co-organising institutions: RIS, New Delhi, who inter alia managed the political clearance from the Ministry of External Affairs, IIM Bangalore, K DISC and the Digital University of Kerala. Our partnering institutions, ICSSR, Kerala State Higher Education Council, Centre for

Development Studies, Kerala Economic Association, and the Centre for Latin American Studies also have been helpful in organising this conference.

With much appreciation for all of you for being with us, we welcome you

K J Joseph
For the local organising Committee

About the 20th Anniversary Conference

The central theme of the 20th Anniversary Globelics International conference is Innovation-driven Knowledge Economies and Transformation in the Global South.

This conference intends to bring together scholars across disciplines from over 50 countries to pool together experiences and expertise to reflect on varied issues involved in the process of transforming developing economies into sustainable, resilient, and inclusive innovation-driven knowledge economies. Episodes of development in economic history highlight the successful experience of countries that have managed to harness Learning, Innovation and Competence-building Systems at the global, national, subnational and sectoral levels in order to transform their social and economic structures for achieving prosperity. In the current times, the constellation of innovations driven by rapid advances in digital technologies has given rise to a new technological revolution, commonly referred to as the fourth industrial revolution, or Industry 4.0, with profound impacts on all sectors of the economies and sections of societies. New and persisting developmental challenges have driven a renewed interest in different types of innovations that highlight their impact on society and the natural environment, such as inclusive innovation, responsible innovation, transformative innovation, grassroots innovation and Jugaad. At the core of all these approaches is how knowledge, both science-based and experience-based, is harnessed for addressing development challenges, the basic premise being “the knowledge divide is at the root of the development divide”

At the current juncture, wherein globalization is at the crossroads, the economies across the world, ravaged by the once-in-a-century pandemic and external shocks, consider strengthening the innovation system as a strategic approach towards building resilience. Evidently, there is an across-the-board drive among developing countries to transform their economies into innovation-driven knowledge economies. Such a transformation is often viewed as capable of building resilience by addressing many of the downsides of globalization-induced high growth, like excessive exploitation of exhaustible resources and accentuated divides within and between countries. Such

initiatives in India are manifested, among others, in Atal Innovation Mission (AIM), Digital India, Skill India, and Make in India and other concerted efforts to transform India into an innovation-driven knowledge economy. It is also in sync with the national agenda of harnessing Science, Technology, and Innovation (STI) to achieve sustainable development. The choice of the location of the conference is inspired by Kerala's strategy towards transforming the state into a knowledge economy, as explicitly stated in the budgets starting with 2020-2021 and the subsequent concerted efforts that followed. It is in this background that Globelics revisits India for the 20th Globelics International conference with the chosen central theme: 'Innovation-Driven Knowledge-Economies and Transformation in the Global South'.

The 20th Anniversary Globelics is also an occasion to celebrate the journey of Globelics from Brazil 2003 to India 2023 and its varied achievements. At the same time, it is also a forum for critically reflecting on our perspective and the approaches *inter alia* in terms of its achievements and limits. This is especially important at the current juncture wherein there is growing disenchantment with the development experience under globalisation on the one hand and the need on the other hand, for reimagining innovation systems in the COVID and Post COVID world towards building the much needed resilience in the South.

Globelics-India 2023 coincides with India's Presidency of G-20 that *inter alia* aims at influencing the development dynamics of Global South and it is an appropriate time for translating the insights of the conference with respect to strengthening Learning, Innovation and Competence-building Systems (LICS) into policy action. For the past two decades, we have observed an increasing influence of Global South in shaping the paradigms and trajectories of the global development agenda—sustainability, climate change, pandemic, and energy security issues—with India playing a key role; all being closely linked to the research domains of the Globelics.

World-leading scholars are set to give this year's keynote address on innovation and development. It is planned that the conference will be inaugurated by the Chief Minister of Kerala and there will be a special keynote on the conference theme along with a Globelics Lecture and Freeman Lecture. The conference will combine plenary sessions, presentations of research papers in parallel tracks, thematic panel sessions or special sessions, poster presentations, book presentation sessions, excursions, and cultural events.

Conference Tracks

While submissions on the central theme of the conference have been especially encouraged, submissions on all the issues conventionally deliberated in the Globelics international conferences are also included. Submissions have been organized around the following themes:

1. Science, technology, innovation: Theory and policy for a knowledge economy
2. Transformative innovation, responsible innovation and mission-oriented innovation
3. Knowledge-driven development of national, regional, local and sectoral innovation systems, including Agricultural innovation systems and rural development
4. Measurement of the knowledge economy: Indicators, data requirements, different approaches and methodologies
5. Skilling for the knowledge economy: Industry-academy interaction, Intellectual property rights, open innovation and development
6. Industry 4.0 and development: Digitalization and automatization, productivity and employment implications, gig economy and quality of employment
7. Economic and social upgrading for sustainable Catch-up: trade policies, FDI, value chains and innovation networks in a knowledge-driven economy
8. Innovation for inclusive development: Indigenous knowledge, Grassroot innovations, Jugaad, informal economy, micro and small enterprises
9. Entrepreneurship, employability and gender dimension in innovation and development
10. The green economy and financing innovation: Low carbon innovations, environmental technologies and renewable energy

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Exploring directionality in a technology intensive sector emerging under resource constraints: The case of medical device innovation and manufacturing in South Africa

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Abstract

The direction of innovation has several developmental implications but is relatively much less studied as compared to its rate. This is even more so with respect to developing countries. With the accumulation of technological capabilities in the Global South, low-middle-income countries are seeking to build strong sectoral innovation systems not only in informal and low technology areas, but also technology intensive sectors. However, the current global innovation dynamics suggest that the path towards developing such capabilities and truly benefitting from their accumulation is riddled with many challenges. Using an exploratory case study analysis of the emerging medical device sector in South Africa and combining a capabilities approach to inclusion with fresh empirical evidence, this research studies how innovations from low-middle-income countries can influence the direction of innovation. Theoretical foundations for this analysis are drawn from innovation studies, frugal innovation, and development scholarships. Grounded in these literatures, the direction of innovation is conceptualised to be inclusive when it leads to accumulation of capabilities both at individual and firm level. The case study discusses the key sectoral institutions, innovation actors and linkages between them, the nature of innovations being generated and processes of innovation diffusion. Further it explores the challenges of the South African medical device sector and its relationship with the broader national innovation system. This research illustrates how despite South Africa's high biomedical research capacity, pockets of innovation excellence and sophisticated manufacturing base, there are many

challenges which make direction of innovation towards inclusion in the medical device sector fragile and difficult to achieve. It shows the important role of the state and multilateral organisations in enabling a more inclusive direction of innovation.

1. Introduction

The direction of innovation has several developmental implications but is relatively much less studied in economic literature as compared to its rate (Fu and Shi, 2022). This is even more so with respect to developing countries. With the accumulation of technological capabilities in the Global South, low-middle-income countries are seeking to build strong sectoral innovation systems not only in informal and low technology areas, but also technology intensive sectors. However, the current global innovation dynamics suggest that the path towards developing such capabilities and truly benefitting from their accumulation is riddled with many challenges (Cirera and Maloney, 2017). This paper seeks to explore through an explorative case study of the medical device sector in South Africa the overarching question: How does resource-constrained innovation influence the directionality of innovation and technological change? Using both primary empirical evidence and secondary literature, this research is a qualitative exploration of this question and examines a technology-intensive sector in developing country context, one that is typically found in well-developed and efficient innovation systems. The choice of medical devices is driven by two factors, the first one being South Africa's innovation capability in this sector. Secondly, the lack of affordable and appropriate medical devices is a global health concern for low-middle-income countries. More than ninety percent spending on health R&D continues to be by high-income countries and is directed towards generating products, processes and services tailored to their own healthcare markets (Global Forum for Health Research, 2004). In addition, the selection also stems from the fact that, there is also interest from high-income countries with rising healthcare budgets in frugal innovation products.

South Africa is a middle-income country, with a sophisticated industrial base, legacy of biomedical innovation and a growing medical device manufacturing sector. However, like many other low-middle-income countries, South Africa is also confronted with challenges of poverty, unemployment, inequality, and economic stagnation. Innovation in South Africa takes place within this context of economic stagnation and complex challenges that have plagued the country for several decades (Kruss, 2020). Any sectoral innovation system, emerging from such an environment, however strong, is confronted, to a large extent, with the typical challenges of the broader national innovation system. This paper seeks to explore how within this resource-constrained context, innovations, sometimes even state-of-the-art, emerge, finding market as reverse innovations in western markets with stringent regulatory

requirements. Further, it examines the knowledge base, networks and linkages, and perspectives of innovation actors including SMEs, university, and government critical to the evolution of a vibrant innovation system.

We theoretically ground our research in in three interconnected streams of literature. The main inspiration is drawn from the scholarships on first, the national innovation systems in developing countries (Arocena and Sutz, 2003; Kaplinsky, 2011; Kraemer-Mbula et al., 2019; Kruss and Lorentzen, 2009; Kruss, 2020; Kruss et. al., 2012; Lema et al., 2021; Lundvall et al., 2009; Srinivas and Sutz, 2008; Sutz, 2007) and second, on frugal innovation (Knorrninga et al., 2016; Weyrauch and Herstatt, 2017; Zeschky et al., 2014; Prahalad and Mashelkar, 2010; Radjou et al., 2012). Together these streams of literature offer rich insights to innovations for and under resource- constraints (Chakravarty and Gomez, 2023) and their implications for development. Third, it brings together literature on directionality of innovation and technological change on inequality (Acemoglu, 2002; Bell, 2009; Chataway et al., 2014; Cozzens and Kaplinsky, 2009; Fu and Shi, 2022; Lazonoick and Mazzucato, 2013; Papaioannou, 2014) and some emerging discussions on pathways for long term development (Andreoni et al., 2021; Chang and Andreoni, 2020; Kraemer- Mbula and Monaco, 2020).

This paper illustrates the wide variety of medical device innovations emerging from South Africa which address both local as well universal health challenges. It shows that while individually all institutions needed for enabling the medical device manufacturing sector are present, they are yet to reach a stage where the system operates in a harmonised manner. Further it illustrates how the broader systemic challenges also affect the sectorial innovation system. For example, development and commercialisation of medical device innovations require synergistic collaborations and complementarities between industry, academia and government. However, the level of cooperation between innovation actors, particularly between industry and academia, is low, reflecting characteristics of the broader innovation system. This paper makes three important contributions. First, it illustrates, the tensions and duality of a technology intensive sector emerging under severe resource-constraints. Second, it discusses the challenges in the evolution of the sector and potential policy interventions needed to overcome them. Third, bringing these findings together it highlights that while resource constrained innovation influences the directionality of innovation towards inclusion, this is highly conditional and fragile.

The rest of the paper is structured as follows: Section 2 offers the theoretical background highlighting the main literature streams shaping our research while Section 3 gives an overview of the methodology. Sections 4 describes the case study and has two sub-sections, one on the national innovation system and secondly on the sectoral innovation system. Section 5 discusses the case study highlighting the important elements of the innovations systems at

various levels, university- industry linkages, and role of universities; and policy interventions to enable the sector. The conclusion Section 6 sums up the key takeaways and proposes future research areas.

2.0 Theoretical and analytical background

2.1 Frugal innovation: Before and now

Frugal innovations are now generally understood as good-enough, functional, and significantly cheaper solutions suitable for resource-constrained settings (Weyrauch and Herstatt, 2017; Zeschky et al., 2014). The antecedents of frugality can be found under the umbrellas of Appropriate Technology (AT) and technological capabilities in manufacturing firms in late industrialising countries (Chakravarty and Gomez, 2023). Inspired by Schumacher (1973) and concerned by the impact of foreign technologies on developing countries, AT scholars were often motivated by ideologies of sustainability, inclusion, and social justice (Cooper, 1974, Kaplinsky, 1990; Singer, 1977; Stewart et al., 1990). The AT movement signalled that “something had gone wrong in the process of choosing technologies” (Stewart, 1987, p.104) and a redirection was needed. The industrialisation and technological capabilities literature (Lall, 1982, 1992; Katz, 1987) documented the assimilation and reproduction of foreign technology mostly for their domestic market by the then called Third World manufacturing firms. These products may be specific to developing country conditions, or “adapted in such a way that many of the ‘frills’ (or high performance, luxury characteristics) are dropped while retaining its essential functions” (Lall et al. 1983, p. 5). These resulted in a South-South technology trade and stimulated a different trajectory of technological change.

Since the emergence of the BoP discourse, MNCs and firms in the Global North have become the central actors in frugal innovation discourse. Frugal innovation been popularised as “doing more with less for more people” and *jugaad* (Prahalad and Mashelkar, 2010; Radjou et al., 2012), the latter a Hindi colloquial term meaning an improvisation or makeshift arrangement to solve problems under conditions of scarcity. Over the years, there has been an evolution in the understanding of frugality and potential customers for these innovations. Moving away from the notion of no frills and “stripped down” solutions, frugal innovations came to be identified as original products specific for resource-constrained settings (Zeschky et al., 2014), sometimes using cutting-edge technology (Rao, 2013). Frugal innovations have become relevant for western markets (Govindarajan and Trimble, 2012; Agarwal and Brem, 2012). In this process of market- based approach to development and poverty alleviation, exploration of innovation and capability accumulation in indigenous manufacturing firms operating under resource constraints, intrinsic to technology and development discourse, have become side-lined. Also less discussed in the dominant frugal innovation discourse is how access can be enabled through public procurement.

2.3 Resource-constrained innovation: For and under

The scarcity-induced innovation heuristics of Srinivas and Sutz (2008), can be applied to draw insights to understand directionality (adaptation illustrated in Figure 1) from a perspective of product or solutions. The upper left-hand quadrant depicts solutions that are available through technology transfer, such as imported machinery, training of workforce, and foreign direct investments including to subsidiaries of MNCs. The benefits of international technology transfer can only be fully realised with complementary indigenous innovation efforts to enhance local knowledge spillovers (Fu et al., 2011; Kesidou and Romijn, 2008). Technological capabilities are the ability to efficiently use technology and in one of the most widely adopted definitions was classified based on functions (investment, production, linkages) and their degree of complexity (routine, adaptive, replicative, innovative/risky), reflecting the deepening of knowledge over time (Lall, 1992). Given the wide difference in contexts such as income, resource constraints, and institutional voids, some technologies from industrialised countries may need substantial adaptation. This represents the bottom left quadrant. FIs in these quadrants when developed by firms in the Global South, are potential reverse innovations and are likely to contribute to South- North technological trajectory. Because of their universal relevance, the innovations in the left quadrants are understood as “frugal variants” of mainstream technological innovations (Chakravarty, 2022). The two right quadrants in Figure 1 represent problems for which solutions do not exist. Firms tend to invest in familiar markets (Christensen, 1997) and in innovations where R&D investments can be appropriated (Levin et al., 1987). Subsidiaries function more to adapt core technologies than to conduct new product development (Gassmann and von Zedtwitz, 1998; Pearce 1999). Therefore, solutions may continue to be absent, either due to lack of investments or lack of market leaving many needs in the developing world (example neglected tropical diseases) and marginalised consumers underserved. Frugal innovations belonging to the right quadrants are likely to contribute to South-South collaboration and trade. For a vibrant sectorial system, innovations in all quadrants need to emerge.

The national innovation system determines “the rate and direction of innovation and competence building emanating from processes of science-based and experience-based learning” (Lundvall et al., 2009, p. 7). Developing countries are characterised by a fragmented innovation system where one or more essential linkages may be missing or underdeveloped. The existence of technology institutions and dedicated resources for their functioning, which are taken for granted in advanced industrialised countries, may be either non-existent or may not perform optimally due to a lack of trained manpower. Technology institutions include agencies focusing on quality, standards, metrology, technical extension, R&D and technical training. Newly created

institutions may take a long time before they are able to operate efficiently. Monopoly by powerful industrialists may block and destroy learning opportunities for small firms. Resources tend to be concentrated in public research organisations and universities in high technology innovations, with less policy attention towards incremental or design innovations in private firms (Bell and Figueiredo, 2012). Industry-university linkages may be weak. The separation of research from development and production capabilities can be very harmful for innovation and development (Malerba and Mani, 2009). With all these challenges, the Schumpeterian dynamics of creative destruction do not work well in these settings (Altenburg, 2009).

Figure 1: Innovation for developing countries

	Problems for which solutions have been found and owned by companies in advanced industrialised countries	Problems for which solutions do not exist many times due to economic reasons.
Problems for which solutions for resource constrained conditions exist	Vast majority of solutions acquired through technology transfer - when developed under resource constraints they are frugal variants of mainstream technological innovations and are potential reverse innovations.	Solutions to problems mainly posed in resource constrained conditions – frugal innovations mainly with market in other developing countries
Problems for which solutions suitable for resource constrained conditions do not exist	Mainstream solutions not suited for resource constrained conditions - when developed under resource constraint they are frugal variants of mainstream technological innovations and are potential reverse innovations.	No available solutions - in areas such as health, example neglected tropical diseases, they become critical development challenge.

Source: Scarcity-induced innovation (SII) heuristic adopted from Srinivas and Sutz (2008)

2.3 Resource-constrained innovation and direction of technological change

The choice of techniques (Sen, 1968; Stewart, 1972) and the direction of technological change have been of concern amongst development scholars since the 1970s. The choice of technology can have competence destroying impacts (Anderson and Tushman, 1990) or create disincentives for indigenous technology development (Dahlman and Westphal, 1982). Technological change resulting from innovation diffusion to contexts very different from their origins is often biased in a direction not always benefiting developing countries (Acemoglu, 2002; Atkinson and Stiglitz, 1969; Basu and Weil, 1998). In a highly interconnected and globalised world, technological change has reproduced and magnified rather than reduced prevailing inequalities (Arocena and Sutz, 2003; Cozzens and Kaplinsky, 2009; Kaplinsky, 2011; Lazonoick and Mazzucato, 2013), bringing directionality of innovation again

to the forefront (Bell, 2009; Cozzens and Kaplinsky, 2009; Fu and Shi, 2022). Intellectual property regimes rigidly enforced by multilateral agreements like TRIPS has led to “intellectual monopoly capitalism” (Pagano, 2014), creating entry barriers for firms in developing countries. Despite the accumulation of technological as well as organisational and dynamic capabilities (Bell and Figueiredo 2012; Dutrénit 2004), it has become difficult for developing country firms to innovate.

The relationship between innovation and inclusion is complex and multidimensional (Papaioannou, 2014) and different pathways to inclusive development have been advanced. Heeks et al. (2014) have argued that inclusion should explicitly conceive development in terms of actively including those who are currently marginalised, taking into consideration inclusion in terms of relevance, in terms of development, ease of absorption, and impact on livelihoods. Recommendations for inclusive innovation policies have proposed greater recognition that science needs to be aligned with pressing social challenges and that research excellence should not be measured by publications (Chataway et al., 2014; Chataway et al., 2019; Kraemer-Mbula et al., 2020). There is renewed policy interest in the demand side of innovation and public procurement of innovation (PPI) as an integrated component of innovation and industrial policy where competing policy agendas of transformative innovation policy and industrial policy can be harmonised (Uyarra, et al., 2020). One line of research has advanced that alongside individual capabilities, which form the core of sustainable development goals, production capabilities central to structural change must also be enabled (Andreoni et al., 2021; Chang, 2010; Chang & Andreoni, 2021). Here, development is understood as a process of sustainable production and structural transformation with quality employment and social inclusion (Chang, 2010; Lema et al., 2021). Building on this, Chakravarty and Gomez (2023) have argued that the direction of frugal innovation is inclusive when both individual capabilities through access and diffusion, and firm level capabilities through innovation and production can be enabled.

3.0 Methodology and data

A dynamic and complex phenomenon such as directionality of innovation is best understood applying an exploratory and qualitative case study methodology (Yin, 2014). A single case study is selected where the unit of analysis is the sectoral innovation system embedded in the national innovation system. This is operationalized by two levels of analysis – a micro-level sectoral analysis focusing on the institutions, universities, and innovative SMEs. Further this analysis is situated and contextualised at the meso- level within the national innovation system in which the sector is embedded. More specifically, we focus on the emerging medical device manufacturing sector in South Africa. There are several reasons for this choice. First, middle-income countries with accumulated capabilities and factor endowments between

industrialised countries and least developing countries are strong candidates for generating intermediate innovations (Fu and Shi, 2022; Fu and Gong, 2011). Secondly, South Africa has a small but growing medical device manufacturing industry. Third, given that South African policies were realigned based on the innovation systems approach, it offers insights into the application of the NIS framework in the developing country context. In recent years there have been several studies on the South African medical device sector (Table 1). These offer rich secondary data for this study. Fourth is the availability of rich secondary data on R & D and business innovation indicators, particularly due to the system of innovation surveys in place carried out by the Human Sciences Research Council.

Table 1: Key secondary literature on South African medical device sector

Reference	Focus
DTI - Deloitte (2014); SAMED-KPMG (2014); SAMRC-PATH (2014); WHO (2016)	<u>Sectoral</u> and landscape reports
<u>Saidi & Douglas</u> (2018); <u>de Jager et. al.</u> (2017)	<u>Bibliometric</u> analysis, collaborations, <u>regulatory</u> changes
<u>Ramaoka</u> , (2020); <u>Ramaoka & Kraemer-Mbula</u> (2021)	Technology transfer and capabilities
<u>Mkwashi</u> (2020); <u>Mkwashi et al.</u> , (2021)	Regulatory capabilities, industrial <u>capabilities</u> , and healthcare
<u>Chakravarty</u> (2022); <u>Chakravarty & Knorrinda</u> (2021)	Innovation driven manufacturing SMEs, <u>frugal</u> innovation

Figure 2 illustrates the overall methodological approach. As a first step, desk research was carried out to understand the sectoral and national innovation system. Subsequently, primary data was collected in three phases of fieldwork, including a pre-fieldwork visit and is based on informed consent to use the data for academic and policy purposes. More than fifty semi-structured interviews were conducted with indigenous firms, universities, and policy makers. Data analysis was carried out in phases over time, beginning soon after completion of the first stage of fieldwork and conducted through an iterative process moving between theory and data (Eisenhardt, 1989). Multiple sources of evidence were used to triangulate findings (Yin, 2014). Directionality requires multiple levels of exploration. Drawing from our theoretical discussion, we identify in Table 2, processes which contribute to inclusive direction of innovation and technological change.

Figure 2 : Overview of methodology



Table 2 : Direction of innovation

Sector Development	Processes contributing to inclusive technological change
Knowledge Base	Innovations relevant for domestic market, challenges and needs neglected by mainstream innovation
Networks	Creation of “frugal variants”
Linkages	Bottom-up product development involving local doctors, health practitioners
Institutions	Industry academia cooperation
Technological capability	Technological efforts by local <u>firms</u>
Dynamic Capabilities	Complex local production and manufacturing
Production Capabilities	<u>contributing to technological capabilities (as opposed to simple assembly)</u>
Regulatory Capabilities	Local procurement of materials, supplies & machinery
<u>Testing, metrology, standardisation etc.</u>	Local design, adaptation and fabrication of equipment
Demand (Domestic, export, import substitution)	Creation of jobs, skill development and training
	Diffusion in the domestic market to replace imported products
	Diffusion through government healthcare delivery and services
	Experimental use of new innovations by government
	South-South trade and collaboration

4.0 The Case

4.1 South African national innovation system

4.1.1 Background

South Africa has extensive science, technology and innovation (STI) infrastructure and institutions founded in the early 1900 to exploit the abundant natural resources in both minerals and agricultural sector. The Department of Science and Innovation (DSI), earlier Department of Science and Technology (DST), is the main institution mandated to provide an enabling environment and resources for STI to boost socio- economic

development. Entities under DST, such as the Council for Scientific and Industrial Research, established in 1945, developed cutting-edge technologies from radars to biomaterials. During the Second World War in the 1940s, the manufacturing sector received a strong boost, replacing mining as the key economic sector. Over time South Africa developed a sophisticated manufacturing base and high-quality public universities and research facilities. In the 1960s, political isolation from the international community due to the apartheid regime necessitated the realignment of science and technology institutions for self-sufficiency in strategic areas. This led to the creation of state-of-the-art R&D and manufacturing in strategic areas like weapons, biological and chemical warfare, not intrinsically linked to building competitive advantage and economic growth (NACI, 2006).

When in 1992, South Africa became a democracy, STI was placed at the heart of the Reconstruction and Development Programme (RDP). The White Paper on Science and Technology (DST, 1996) was amongst the several important policy documents progressively released to enable the country's transformation to a more inclusive society. The White Paper was designed adopting the national innovation systems framework at a time when the NIS literature was still embryonic and focusing on industrialised economies (Lorentzen, 2009). The other policy document, the National Research and Development Strategy (NRDS) in 2002, identified some priority sectors, for government funding, with an investment target of 1% GERD¹ of the share of GDP. Biotechnology, information technology and natural resources were identified as priority areas of research and innovation focus.

4.1.2. Current NIS characteristics

Despite its many strengths and capabilities, South Africa has emerged as a dual economy shaped by the country's colonial and apartheid legacy, facing triple challenges of poverty, inequality, and employment (Tregenna et al., 2021). Premature deindustrialisation has negatively affected the economy, and the export structure remains characterised by commodities and mining products, which have limited spillovers for learning and building innovation capabilities. Adequate processes of structural transformation, moving to sectors with high productivity and complexity, and upgrading to value-added innovative activities within these sectors has not happened (Andreoni et al., 2021). Weak economic performance has resulted in negative per capita GDP growth in recent years. Manifestations of its unique history, coupled with economic choices, have resulted in poor levels of structural transformation and unsustainable, non-inclusive growth (Tregenna et al., 2021). There are many challenges in the innovation system. Some of the most critical of these include, on the one hand addressing poverty and joblessness in the informal economy and tackling inequalities in race, gender and age in higher education while, on the other hand, attracting investments in the face of the growing shortage of its technical skill gap in a globalised world (NACI, 2006). Many of

these challenges are rooted in South Africa's apartheid history. Diverse types of universities were established for specific purposes and segregated based on racial and ethnic profiles (Kruss et al., 2012). Access to quality education, isolation and restrictions in mobility to access better quality education and other opportunities for a century prevented the accumulation of skills necessary for the modern labour market (NPC, 2011) and has resulted in an acute skills shortage.

R&D and business innovation surveys are conducted periodically by the Centre for Science, Technology and Innovation Indicators (CeSTII) of the Human Sciences Research Council (HSRC) on behalf of the DSI. In recent years, GERD in South Africa has further fallen, and there has been a sharp decline in R&D in the business sector within the context of economic stagnation (HSRC, 2020). Table 2 summarizes some of the indicators from the most recent business innovation survey carried out between 2014-2016 revealing the many challenges. Lack of funding is a key innovation barrier, and most businesses relied on their own funds to innovate. Very few were aware of or received funding from the South African government. Also, innovation is not collaborative, where suppliers of equipment, materials and software were the most highly valued partners with very weak links to government research institutes and universities (HSRC, 2020). Firms are reported to value internal sources of knowledge, clients and suppliers more than universities and government laboratories which represents a small percentage of their information source. Market factors are also another key barrier. Businesses were aware of government support for innovation, but innovation is not linked to public sector procurement. On the positive side, the survey also suggests that almost three-quarters of businesses in South Africa are innovation active and practise multiple forms of innovation. Recognising the importance of imitative, frugal, and incremental innovation, as well as design and engineering activities, within its developmental context, South Africa's recent White Paper on Science, Technology and Innovation (DST, 2019) has also adopted a broader conceptualisation. The White Paper has also proposed to strengthen the focus on demand- side innovation through co-funding, public procurement and sectoral innovation funds, working in collaboration with other government departments.

4.2 Medical device sectoral innovation system

4.2.1 Institutions

South Africa is one of the largest medical device markets in the Middle East and Africa region. Like any other developing country, South Africa's medical technology needs are met primarily through imports. The country imported almost 13.5 USD million worth of medical devices, one- fifth of which was from the US (SAMRC, 2022). There is a perception that South Africa is uniquely placed to develop its medical device manufacturing, contributing

towards the National Development Plan 2030 by using it to improve its healthcare and economic condition (SAMRC- PATH, 2014). Since 2008, several reports have been published on South Africa's medical devices sector. The latest of this is a landscape survey conducted by the South African Medical Research Council (SAMRC, 2022).

"Most, if not all, of the building blocks are in place for a strong and vibrant medical devices industry in South Africa, driven by a combination of local innovations emerging from STI institutions, both high and low technology capabilities within existing companies to produce a diverse range of high-quality products suitable for the local and export markets, and ongoing efforts to replace specific imports with locally produced devices" (SAMRC, 2022, p.13).

Indeed, most key institutions necessary to support the medical devices sector are in place. Table 4 offers a list of some of the key institutions with a brief explanation of their functions. There are also a variety of support and funding instruments, many jointly implemented by different government departments. Most recently, in an effort to strengthen the sector through a cluster- based approach, the Medical Devices and Diagnostics Innovation cluster (MeDDIC) has been launched. The cluster is a national initiative supported by TIA and DSI and hosted by SAMRC and will have three core areas of focus aimed at integrating the innovation system, localisation and rapid product development and human resource development. Currently, the local medical device manufacturing sector is faced with many challenges. Some of the main issues reported relate to regulation and certification, funding, the dominance of multinational corporations, lack of preferential procurement for local manufacturing and prioritisation of price over quality (SAMRC, 2022). There is currently no preferential procurement for local manufacturing, so firms face direct competition from imported products and foreign companies. Broad Based Black Economic Empowerment (BBBEE) regulation which determines access to the public market does not offer sufficient incentive for local manufacturing and innovation (SAMRC, 2022). The passing into law of the Medicines and Related Substances Amendment Act 14 of 2015 and the subsequent establishment of the South African Health Products Regulatory Authority (SAHPRA) by the government are milestones. Prior to the Medicines and Related Substances Amendment Act 14 of 2015, SA did not have a comprehensive regulatory framework that governed medical devices. However, with many enabling institutions in the process of restructuring and transition, such as SAPHRA, offer a formidable challenge to the industry (Saidi and Douglas, 2018).

4.2.2. Research capabilities and university led innovations

South Africa has a legacy of biomedical research, particularly in the Western Cape and Gauteng province. There are two universities, both in the Western

Cape, with dedicated biomedical engineering divisions. The University of Cape Town's (UCT) biomedical engineering division completed its fiftieth anniversary recently. Its history in biomedical engineering together with the Groote Schuur Hospital, a premier academic hospital located in close geographic proximity, can be traced back to the 1950s. The first activity in the field was the work in nuclear medicine by Allan MacLeod Cormack, that eventually led to computer-assisted tomography and the Nobel Prize in Physiology or Medicine in 1979. The other is the Institute for Biomedical Engineering of Stellenbosch University, which has been founded recently but has emerged from the Biomedical Engineering Research Group started in 2005. A new Biomedical Research Institute (BMRI), which will be based at Stellenbosch University's Faculty of Medicine and Health Sciences (FMHS) Tygerberg Campus, is being set up. Both these universities have active and well-established technology transfer offices for the commercialisation of research. They have enabled the formation of a cluster of innovative medical device firms in the Western Cape region. While not as prominently as these two, other universities such the Witwatersrand University and the University of Pretoria also have enabled biomedical-related innovations and technopreneurs (Chakravarty, 2022).

A thriving micro innovation ecosystem has emerged from the UCT - Groote Schuur academic hospital with many cutting-edge products², as well as innovations from the Frugal Biodesign lab. We discuss three spin-offs, in various stages of maturity. Cape Ray, which has its origins in African Medical Imaging (Pty) Ltd (AMI)- a joint venture company set up by the University of Cape Town and De Beers to exploit a low-dose X-ray (LODOX) for medical diagnostic imaging is one such example. Founded by a professor of Biomedical Engineering at the university, Cape Ray, which was formally registered in 2010, is in the advanced stage of commercialisation with its innovation which can detect early stages of breast cancer in a single device. In South Africa, the Department of Health has not adopted breast cancer screening as a priority, and there is no screening programme. Therefore, the potential first use of the product in the domestic market is in private hospitals. However, the application of the product is universal, and the product offers export potential. Cape Ray is ISO 9001 and ISO 13485 certified and owns several US patents. Strait Access Technologies (SAT)³ founded in 2008 by a small team of clinical, biomedical and polymer scientists each with decades of experience, numerous international patents and academic collaborations across the globe. SAT develops intelligent surgical products for rheumatic heart disease, which has been declared by WHO as a global health priority. Its second-generation balloon-expandable TAVI⁴ valve is designed to treat the entire aortic valve disease spectrum making it relevant to developed countries as well. It is housed within the Cardiovascular Research

Unit⁵ in UCT and has a highly specialized state-of-the-art research and production facility. While many of SAT's high precision equipment are imported, some have also been designed and fabricated locally which have substantially reduced the time for procurement as well as cost. The Frugal Biodesign lab, in UCT was set up by a professor who is himself a prolific innovator. The lab "aims to understand innovation in the context of resource-restricted environments, local conditions and the needs of the appropriate 'user' – that is, the clinician"⁶. One of the successful early-stage start-up which has emerged from this lab is Impulse Biomedical. Impulse has developed two innovations, the ZibiPen and the Easy Squeezy, which are in different stages of development and clinical trials. The Easy Squeezy was the result of a prompt from a professor at the Red Cross War Memorial Children's hospital to solve the challenge of the non-use of inhalers by children, making them inappropriate for paediatric use⁴.

All the above three start-ups managed to secure funding. Cape Ray secured funding from the National Institutes of Health (NIH) in 2005 and IDC in 2009 based on IP developed by its parent company. The firm is also making use of the Department of Trade, Industry and Competition's THRIP and TIPTOP funds. SAT has received a grant from TIA and venture funding from Bidvest, a South African investment firm. Impulse has received several awards for their innovations, including from the SAB Foundation, TIA, UCT and MERCK Accelerator, amongst others. Recently the firm has managed to secure funding from South African based asset management company, Futuregrowth, making Impulse the first pre-revenue start-up that the company has invested in. There have been initiatives by the South African government and university technology transfer offices to enable the commercialisation of research for many years in the past. For example, Acorn Technologies, a public-funded virtual incubator, was launched in 2002 under a joint program between DST, DTI and European Union (EU). Acorn operated as a non-profit, managing to identify and mentor early-stage entrepreneurs having technologies with both health and economic impact (Chakma et al., 2010). Venture capital funding in South Africa is conservative with most funding post revenue, whereas it is needed pre-revenue for start-ups. Universities are trying to bridge this gap by setting up funds such as the Evergreen Fund and the University Technology Fund.

4.2.3 Innovation driven manufacturing SMEs

South Africa's medical devices sector is dominated by multinational corporations mainly selling imported and assembled products. The country serves as an entry port for these firms looking to do business in African countries through distributorships (Ramaoka, 2020). But most R&D and product development is conducted in MNC headquarters (Mkwashi et al., 2021), who mainly take advantage of South Africa's strength in manufacturing and clinical trials but are not involved in strengthening local capabilities

(Motari et al., 2004). However, there is also a small but growing medical devices manufacturing sector comprising of local companies mainly. The main products being manufactured locally are IVD (in vitro diagnostic) products, implants (orthopaedic, cardiac, dental etc.) and surgical devices. In comparison to Ethiopia, Nigeria and Tanzania, South Africa has the greatest manufacturing capacity, with many medical devices already being produced locally (WHO, 2013; WHO, 2016). Most of these manufacturing firms are small competing against MNCs which employ a large number of people and struggle with many challenges such as access to funding, compliance with regulations (Chakravarty, 2022; Mkwashi et al., 2021; Ramaoka and Kraemer-Mbula, 2021). In an in-depth study on regulatory capacities in the medical device sector, Mkwashi et al. (2021) note that one of the biggest regulatory constraints is the lack of calibration authorities, with firms having to send equipment overseas making the process prohibitively expensive.

In contrast to its rich biomedical research capability, the number of successfully commercialised products is still limited (Chakma et al., 2010). While these are not in large numbers, there are a few innovation driven medical device SMEs and some state-of-the-art medical device innovations have also been documented (Chakravarty, 2022; Ramaoka, 2020). Many of these firms, such as the Sinapi Biomedical's "Ellavi" – a device to arrest post-partum haemorrhage and Shonaquip's paediatric wheelchairs, are products specifically oriented towards addressing problems specific to low resource settings. In some cases, collaborations with the South African government and global non-profits such as PATH have made devices accessible through public delivery system. Locally designed and fabricated equipment replacing imported ones, inhouse manufacturing and testing facilities to overcome institutional voids and lack of technology infrastructure and services to reduce cost exist represent both frugal and inclusive processes (Chakravarty, 2022, Chakravarty and Knorrinda, 2021). Multiple sources of knowledge, both domestic and international, through formal and informal partnerships, complementing inhouse R&D capabilities make these firms important nodes of the innovation system. This combination of imported technologies and the creation of new ones is critical in building the national innovation system (Muchie & Bhaskaran, 2009). Many products are exported not only to other emerging markets but also to developed markets with stringent regulatory barriers clearly illustrating South Africa's pockets of innovation excellence. Ramaoka and Kraemer-Mbula (2021) observe contradicting views among stakeholders, where firms cite a lack of access to the domestic market and policy support disabling the sector while government agencies arguing that necessary support is in place for firms to thrive.

5.0 Discussion

5.1 Characteristics of sectoral innovation system

While most of the key sectoral organisations are present, many structures are being established or in transition and are not yet in a stage where they can implement their mandates fully. Development and commercialisation of medical device innovations require synergistic collaborations and complementarities between industry, academia, and government. As per South Africa's business innovation survey, the level of cooperation between innovation actors, particularly between industry and academia, is low (Table 3). Less than 10% of these innovative businesses partnered with research institutes and universities, with universities of higher scientific repute are less motivated towards industry collaborations (Kruss and Visser, 2017). Within the medical devices sector, a study by de Jager et al. (2017) has also confirmed a lack of domestic collaborations, including academia, healthcare, and industry. Suppliers of equipment, materials, components, and software are the most valued partners for collaboration (HSRC, 2020). Highly skilled local suppliers are catering to university start-ups to replace state-of-the-art imported equipment as well as working with industry are clearly present in the medical device industry. They represent an important link in the knowledge flow between industry and academia.

Even though industry-academia, collaboration is low, some observations show promise if nurtured. For example, a sense of goodwill and cooperation between local industry and academia was observed, sometimes at the individual level, even when there was no existing formal R&D cooperation. Many forms of exchanges exist. While the industry offers internship opportunities, contributes as evaluation committees and curriculum development, and guest lectures; academia and public research facilities offer scientific advice, clinical trials, and prototype development facilities in addition to a trained workforce. Further, within the medical devices sector, there are champions (including from the government) who have been working to further local manufacturing for many years and are well respected in the community. Academic hospitals play a vital role in the innovation development process, and in the South African context, these too have been closely involved in pre-clinical and clinical trials and played a critical part as highlighted in the UCT-Groot Schuur innovation ecosystem.

In a country with critical skill shortages, a challenge noted in many of the sectoral reports, many of the firms interviewed remark on the quality of engineers available in South Africa. For example, a mature firm with a diverse product portfolio including patented technologies noted how very good students chose to pursue biomedical engineering, and due to limited employment opportunities, local firms were able to employ good candidates. However, it is not always easy to find the right set of skills within the

requirements of BBBEE. Complementary views were echoed from academia, noting that: *“Biomedical engineering is a fascinating space because everybody wants to change people’s lives, and they see biomedical engineering as a shorter route to do that. The demand for the program is extremely high. But we don’t want to flood the market with too much. There’s no job market, so people end up working in other industries”*⁷. Therefore, universities are successfully fulfilling the needs of the industry in offering skilled workforce, while also being strategic not to oversupply labour for an industry which is still underdeveloped.

For many firms, including spin-offs, as they grow in maturity, collaboration with university and public research organisations becomes less prioritised. One of the reasons preventing greater cooperation for more mature firms lay in differences in underlying motivations, incentives, and pace of work, because *“research is slow”*, clarifying, *“We have very good relations, but what happens with universities is they work according to an academic year, so you can’t force a timeline on a university, and we have to innovate very quickly, so that has been problematic for us”*⁸. Low level of cooperation between industry and academia is not a situation specific to South Africa, rather a feature found in many developing country innovation systems. Fischer et al. (2019), who study the critical role of university-business cooperation in promoting frugal innovation with empirical evidence from Brazil, also observe how the slow bureaucratic processes within academia (and government) are a disincentive to companies.

5.2 Sectoral - national innovation system relationship

The relationship between national and sectoral innovation system has an important effect in shaping the sector. Some sectoral systems become predominant in a country because the existing institutions of that country provide an environment more suitable for certain types of sectors and not for others (Malerba and Mani, 2009). The African context is typically characterized by several big powerful businesses in trading, construction and services whose interests many times conflict with the few manufacturing industrialists and SMEs with limited capacities to scale (Andreoni, 2019). Supporting extractive industries over manufacturing in the past twenty-five years has resulted in limited economic diversification and structural transformation (Andreoni et al., 2021). The nature of economic growth is not pro-poor and generates an insufficient number of jobs (World Bank, 2018). Further, as Mkwashi et al. (2021) note, South Africa has developed a distribution infrastructure based primarily on imported medical devices which for a long time had limited regulation requirements. It is within this environment that the medical device sector operates.

There may be situations where national institutions may constrain the development or innovation in specific sectors. For example, one of the reasons stated demotivating industry-academia cooperation pertains to some of the complications emerging from the IP Act for public funded research: *“There is*

lot of issues around sub-contracting to universities, and they tightened up the IP issues a lot in South Africa. So, you can't go into an agreement with a university, then by law they own the IP, and you have to be very careful that you don't lose the rights to your own. [...] We funded research and then a masters student leaves and becomes our competition, obviously they also have to utilize what they have learnt in their studies, but we have to protect our intellectual property"⁹ Making the situation trickier as a respondent in academia points out that it is difficult to know upfront what patentable innovations are going to emerge and how such an agreement would look like. In line with the role of patents as reassuring potential investors noted in literature (Kahn, 1991), researchers and university spinoffs viewed IP as critical for bringing in venture capital funding and other investments: "if you're looking at that sort of investment period for that period of time, you need to have something concrete so that somebody will be able to invest. To last that long there needs to be some form of credibility"¹⁰. Despite high research capacity in healthcare and biomedical field, "research is almost exclusively publication driven rather than also focusing on innovation and product R&D" and commercial exploitation of IP remains low (SAMRC-PATH, 2014, p. 7). In South Africa, very few businesses protect or profit from IP, and the prevalent strategies of protection are trade secrets and confidentiality agreements (HSRC, 2020). Few firms interviewed in this study also stated that they would use other forms of knowledge protection or a selective patent strategy.

5.3 Directionality of innovation and implications for policy

"The domestic manufacturing industry is caught between two major forces. Firstly, the high-end portion of the market is dominated by an incumbent regime of global companies headquartered in developed countries. Secondly, the lower end of the market is dominated by a similarly powerful incumbent regime that supplies cheap imports from China, India and other developing countries" (SAMRC, 2022, p.92).

The above excerpt from the latest landscape analysis sums up the unique position of South Africa's medical devices manufacturing sector. However, there are also untapped spaces offering a window of opportunities. as an interviewee points out, "a lot of the products gets very stiff competition from cheap imports, but in the specialised sector of the market there is still scope"¹¹. The orientation of innovation from both universities and firms indicates a wide spectrum addressing problems of both developing and developed countries, conforming to all quadrants of the SII heuristics discussed in Fig.1. There seems to be a deep awareness of resource-constrained needs and specificities. With a focus on high-quality research, high-impact publication, and institutional structures to commercialise university research, support is skewed towards universities and spin- offs. While new schemes such as the University Technology Fund have emerged to support universities, funding for firms continues to be low and characterises the innovation system. There is a low level of funding support for incremental innovation or activities not

strictly recognised as formal R&D or activities which are not likely to result in patents. This is not synchronous with many aspects and needs of the South African innovation system where firms tend to protect intellectual property through trademarks and know-how and practise all forms of innovation (HSRC, 2020). The current mode of R&D funding of radical innovations does not match many medical device innovations which are design and engineering based involving incremental innovations. Further, it is not able to capture shop floor process frugal and inclusive innovations such as design and fabrication of equipment and components to replace state-of-the-art imported equipment. This pattern of innovation funding has resulted in poor levels of support to firms, not emerging from university settings and is not conducive to building firm level productive capabilities.

For innovations from universities, most examples discussed in this research are still in their early stages, and therefore it is too premature to know if they will go on to contribute to the accumulation of production capabilities. There have been a few cases such as Lodox and Altis Biologics discussed in Chakravarty (2022) which have emerged from university environment and have become established manufacturing firms. But mostly, R&D remains separate from production capabilities. Without the integration of research, development, and production capabilities, on one hand firms remain without any production capabilities and others rely too much on external research but do not have any internal R&D capabilities (Malerba and Mani, 2009), creating a lack of complementarities (Bell and Figueiredo, 2012). It could be expected that the new White Paper (DST, 2019), which identifies the need to broaden the concept of innovation to extend it to activities such as incremental innovation, design, and engineering etc., will set the scene for new policies in this direction. Also, given that one of the areas of focus of the newly launched Medical Device and Diagnostic Innovation Cluster (MeDDIC) is localisation and rapid product development, it can be expected that innovation in manufacturing firms will see more support in future.

One of the key aspects of directionality of innovation towards inclusion is access in low- and middle-income countries. Public procurement of innovation (PPI) as an integrated component of innovation and industrial policy has been viewed as an instrument that can harmonise the competing policy agendas of transformative innovation policy and industrial policy (Uyarra, et al., 2020). Some cases such as the use of Ellavi, paediatric wheelchairs, monitoring of hearing loss in decentralised MDR TB programme (Chakravarty, 2022) illustrate success where this dual role has been achieved, including where the state has acted as an experimental user (Malerba, 2007). However, these are limited in number. Mirroring its dual economy, even though its healthcare expenditure is 8.5 % of GDP (in 2015), less than half of this is spent on 84 % of the population, who mostly use public health services, whilst 4.4 % is spent on the rest of the population (Fusheini and Eyles, 2016). Therefore, for a country

where over 80% of the population is dependent on public health, it is only through public delivery that will enable access to those who need it most. Within an environment dominated by multinational corporations, new regulatory requirements, BBBEE regulation determining access to the public market and lack of preferential procurement for local manufacturing, South African SMEs struggle to find access to the domestic market through the public delivery system. The new White Paper (DST, 2019) has proposed to strengthen the focus on demand-side innovation through co-funding, public procurement, and sectorial innovation funds, working in collaboration with other government departments. However, public procurement is a highly technical (and political) process requiring consideration of both immediate costs and of health priorities as part of longer-term development goals and of building innovation capabilities (Chataway et al., 2016). For medical device frugal innovations in cases where no equivalent product exists or procurement is based only on imported standardised products, it may involve adjustment or introduction of standards and regulations, a time consuming and complicated process.

6.0 Conclusion

South Africa is uniquely positioned to design devices across the innovation spectrum and address the challenges of both developed and developing countries, as the examples cited in this study illustrate. Despite islands of innovation activity in South African businesses and research excellence, its triple challenges of poverty, inequality, and unemployment rooted in colonial and apartheid past, along with overall economic stagnation, do not offer a conducive environment for innovation to flourish.

One of the core messages emerging from this research is the tension and challenge between the broad NIS and the sectoral innovation system. These tensions and challenges are closely related to scarcity-induced innovations in developing countries and can be vividly observed in South Africa at various levels. For example, on the one hand, it is a middle-income country and an OECD member. On the other hand, its triple challenges of poverty, inequality and unemployment complicated within a context of economic stagnation make R&D and innovation support a secondary priority. While innovation in South Africa is quality-driven, public procurement is driven by price over quality. Even domestic manufacturing is caught between a market dominated by companies from developed countries and Chinese and Indian products. Further, while policy regulations like BBBEE add to the cost of production, affirmative action is recognised important for undoing historical injustices.

Bringing together the various observations from the case study and drawing on our theoretical foundations where we have conceptualised inclusion in directionality when both individual capabilities and firm level capabilities are enabled, we advance the following argument in response to the overarching

research question. When indigenous firms innovating under resource constraints play a central role in the design and production of innovations for resource constraints, the process contributes to technological capability building and development of frugal innovations. Inclusion happens through more participative and bottom-up processes of product development and production of innovation. Inclusion also happens because the frugality in the processes is also embodied in the product characteristics – for example, in price, appropriateness of technology or incorporating views of local healthcare workers. When these innovations for resource-constrained contexts are made available to domestic and other developing country markets, and especially when diffused through public delivery, they contribute to the development of individual capabilities of the marginalised. Inclusion happens through access to erstwhile unavailable products and services and is of particular relevance when it is in areas of basic needs. Together these two processes contribute to a direction of technological change that is more inclusive. A case where this has happened is in the development of the uterine balloon tamponade as well as for the design and diffusion of paediatric wheelchairs by South African firms. In order for this to happen, high innovation capabilities (technological, production and organisational) are a pre-requisite, and these have been built only by a few firms in South Africa over time. When these innovations are also relevant to developed countries, alternate pathways of technological change emerge. However, the relationship between resource-constrained innovation and development is subject to multiple conditions, and the direction towards inclusion is fragile.

First there is the decision at the level of the firm to invest in innovation for resource constrained environment. Then there are difficulties in the diffusion of innovation through public delivery. With too much resistance, firms under resource constraints could become oriented to innovate only for exports interested in “frugal variants” of innovations with universal relevance. Then the path creating technological change may come at the expense of inclusion. Also, in order to overcome inefficiencies in the local environment, innovation under constraints can happen in an enclave, including bypassing domestic collaborations to focus on international linkages. When this happens, spillover becomes limited. These are just some of the instances to show the fragility of inclusion in the directionality of innovation. The role of the state and policy interventions at multiple levels remains critical to ensure that the direction does not reproduce and aggravate inequality and exclusion.

An area of policy consideration is that existing sectoral reports do not sufficiently acknowledge the differences in characteristics and, therefore, spillovers between start-ups and mature manufacturing firms. For example, the impact on the innovation system from productive enterprises with high levels of organisational capabilities, which have been accumulated over many years of operation, is under recognised vis-à-vis the importance given to high

biomedical research capability and patents. In a country with crippling unemployment, these manufacturing firms create high levels of quality jobs while also training and absorbing less skilled labour. Future research and policy discussions could take into consideration the distinctions between the characteristics and impacts of the different types of firms and innovation. For a dynamic medical devices sector to emerge, support to both industry and spin-offs, radical and incremental innovation would be needed to enhance complementarity. Another area where policy intervention could be important pertains to the presence of local suppliers highly skilled in the design and fabrication of high precision equipment and components. Given South Africa's design and engineering strength, this ancillary sector could itself emerge as a promising industry offering frugal versions of mainstream equipment from mainstream medical device manufacturing firms.

In line with earlier sectoral reports, we also agree that these challenges can only be addressed with strong political commitment and aggressive policies. However, what is also evident from the case study is that the challenges are multiple and influencing the direction of innovation towards inclusion is not straightforward. Potential area of future research is a better understanding of the role of universities and what kind of industry-academia linkage can best contribute to enhancing capabilities and local knowledge spillovers in the medical device sector. The works in the biotechnology sector by Kruss (2012) in South Africa and Sutz (2007) in Latin America offer good starting points. Such a study would also be important within the broader conversations about how research excellence and societal impact may be brought together in developing countries.

Table 3 : Characteristics of business innovation in South Africa

<i>Nature of Innovation</i>	
Innovation active businesses	~ 70%
Level of engagement in different types of innovation activity	~ Equal in all four (product innovation, <u>organisational</u> innovation, marketing innovation, and process innovation).
Sectors with highest concentrations of innovation	Engineering and tech, manufacturing, <u>trade</u> .
<u>Innovation outcomes</u>	<u>Incremental, not radical.</u>
	Marginal immediate impact on turnover
<u>Most important innovation outcome</u>	<u>Quality improvement.</u>
<u>Intellectual property rights.</u>	Trade secrets or confidentiality agreements most preferred.
	Very few <u>capitalise IP</u>

<i>Government support (in innovation active businesses)</i>	
Awareness of government financial support	33.6%
Own source of funds to innovate	77.0%
Government as a source of funds	1.7%
Public procurement contracts	(21.9%), 32.3% of these contracts required innovation.
Major obstacles to innovation	Excessive cost of innovation, lack of credit, difficulty in accessing government grants. Market factors
<i>Collaboration in innovative businesses</i>	
Collaboration activities as part of innovation development	20.8%
Most valued information sources	<u>Within</u> a business group (45.6%) clients (37.8%); suppliers (30.8%).
Less valued information sources	Private research institutes (7.4%) Government research institutes (7.8%) Universities and higher education institutions (2.8%)
Value in external partners	Suppliers (19.2%) clients (16.6%) <u>Competitors</u> (14.6%). Government (10%), Research institutes (8.0%), Universities (6.8%), Private research institutions (4.9%)

Source: Compiled from Business Innovation Survey (2014 – 2016) HSRC, 2020

Table 4: Key institutions in the South African medical devices sector

Department of Science and Innovation (DSI): Earlier Department of Science and Technology (DST), it provides an enabling environment and resources for science, technology and innovation to boost socio- economic development. DSI has several entities under it such as the Council for Scientific and Industrial Research, the National Research Foundation, the Technology Innovation Agency, the Human Sciences Research Council, the National Advisory Council on Innovation, and others, to achieve its objectives.

Council for Scientific and Industrial Research (CSIR): offers research infrastructure and conducts directed, multidisciplinary research and technological innovation aligned with national priorities, which are undertaken through its many dedicated divisions. CSIR has developed and offers licensing of several technologies and also provides services to the industry for metrology and testing.

Technology Innovation Agency (TIA): Funding institution to bridge R&D and commercialisation (up to pre-commercialisation). It has a Health Biotechnology Unit to support technological innovations in the diagnosis, prevention and treatment of priority diseases. In addition, through its Innovation Skills Development (ISD) unit, TIA supports business and entrepreneur development.

Department of Health (DoH): Mandated by the National Health Act of 2003 for the provision of a structured and uniform health system. Entities of DoH include National Health Laboratory Service, South African Medical Research Council, Council for Medical Schemes, South African Health Products Regulatory Authority and others. It is the main agency for public procurement of medical devices. Respective provincial departments are responsible for healthcare delivery at the local level while working under the national umbrella.

South African Medical Research Council (SAMRC): mandated to improve the health of the population, through research, development and technology transfer, for a better quality of life. Operates Strategic Health Innovation Partnerships (SHIP), in collaboration with DSI, to fund and manage innovation projects, including medical devices. SHIP forms part of the Grants, Innovation and Product Development (GIPD) directorate. Also hosts the newly launched Medical Device and Diagnostic Innovation Cluster (MeDDIC).

South African Health Products Regulatory Authority (SAHPRA): established replacing the Medicines Control Council (MCC), following the Medicines and Related Substances Amendment Act, 14 of 2015, and is the central authority governing the import, purchase, use, etc., of medical devices. No medical device may be manufactured or marketed without a SAPHRA license.

National Intellectual Policy Management Office (NIPMO): entity under DSI makes provision to identify, protect, utilize, and commercialise IP from public-funded research (IPR Act 2010) for the social and economic benefit of South Africa. The Act provides for the university to own the IP that was developed by researchers of the university, joint ownership between the university and private sector for cofounded projects and contract research, where the IP Act does not apply. In order to assign IP, approvals from NIPMO are needed. Universities are legislatively mandated to share the benefits of IP commercialisation with the IP creator.

Department of Trade, Industry and Competition (DTI and C): It has several entities, and a variety of funding instruments, such as (a) Technology and Human Resources for Industry Programme (THRIP) provides funding to firms to meet their technology needs in collaborative projects with universities. (b) Technology Innovation Promotion through the Transfer of People (TIPTOP) to facilitate mobility between industry and academia. (c) Support Programme for Industrial Innovation (SPII) focuses on technology in the development phase.

(d) Manufacturing Competitiveness Enhancement Programme (MCEP) supports firms to raise production and retain jobs. Within this, the Industrial Policy Niche Projects Fund supports strategic new areas with the potential for job creation, diversification and exports that would otherwise not be candidates for commercial funding. (e) Support for the industry to participate in exhibitions.

Industrial Development Corporation (IDC): An entity of DTI and C, it is a self-financing, national development finance institution with the objective to contribute to sustainable economic growth and economic empowerment through entrepreneurship in competitive industries.

South African Medical Technology Industry Association (SAMED): Earlier South African Medical Devices Association industry association founded in 1985, primarily representing MNCs.

Medical Device Manufacturers of South Africa (MDMSA): industry association mainly of local manufacturing companies and association members of SAMED. MDMSA exists to grow the locally manufactured content of this industry sector within South Africa as well as equip our members to compete internationally. It interfaces with the different government departments to leverage the various mechanisms for growth, compliance, export and innovation Support.

Western Cape Medical Devices Cluster (WCMDC): established in 2016 in partnership with the Department of Trade and Industry, WESGRO (Cape Town and Western Cape Tourism, Trade and Investment) and the Western Cape Government. Has seven founding local manufacturing companies.

University Technology Fund (UTF): Launched by SA SME Fund in 2020, a first of its kind in Africa, is an IP commercialisation fund for IP originating from universities. UCT and Stellenbosch University are the first universities participating. It also offers smaller amounts for very early-stage investment in order to develop the pipeline.

South African Breweries (SAB) Foundation: An independent trust towards developing entrepreneurship in South Africa set up in 2010 as one element of SAB's broad-based black economic empowerment initiatives and was the first organisation to receive tax exemption and is registered as a tax exempt Small Business Funding Entity under the Income Tax Act.

Source: Compiled from respective websites by Authors.

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Notes

- ¹ Gross expenditure on R&D. Under the apartheid regime, GERD was about 1.2 or even higher, but spent on military dominance and energy sufficiency in the interest of the white minority (NRDS, 2002).
- ² A similar innovation cluster exists around Stellenbosch University, but this is more widely spread out, vis-à-vis the close proximity of the UCT-Groot Schuur ecosystem.
- ³ SAT was earlier called Percutaneous Technologies.
- ⁴ Trans catheter aortic valve implantation (TAVI) is a minimally invasive procedure where a new valve is inserted to replace the damaged valve without removing it.
- ⁵ This unit is housed in the Chris Barnard Building, named after South African surgeon who performed the world's first human heart transplant at Groot Schuur hospital in 1967.
- ⁶ <http://www.health.uct.ac.za/news/easy-squeezy-asthma-device-children-and-aged> [Accessed on 18 June, 2022]
- ⁷ Interview (University, September 2019).
- ⁸ Interviewee (manufacturing firm, March, 2019)
- ⁹ Interviewee (manufacturing firm, March, 2019)
- ¹⁰ Interview (University, September 2019)
- ¹¹ Interview (manufacturing firm, March 2019)

The STEM pipeline in India: Challenges ahead

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Abstract

The term "STEM pipeline" refers to the educational and career pathway that individuals can follow to enter and advance in the fields of Science, Technology, Engineering, and Mathematics (STEM). The pipeline represents the various stages and transitions that a person goes through to become a successful professional in a STEM-related field. The STEM pipeline typically begins with K-12 education, where students learn the foundational concepts and skills that are essential for STEM fields. This includes subjects such as mathematics, physics, chemistry, biology, and computer science. After completing high school, students can pursue undergraduate and graduate degrees in a STEM discipline at a college or university. During this phase of the pipeline, they gain more in-depth knowledge and specialized skills in their chosen field. After completing their education, individuals can enter the workforce and pursue a variety of career paths in STEM fields. These can include jobs in research and development, engineering, information technology, healthcare, and many others. The STEM pipeline represents individuals' journey to develop the knowledge, skills, and experiences necessary to succeed in STEM-related careers. It is an ongoing process that requires continuous learning and adaptation to keep pace with the rapidly evolving world of science and technology.

India needs to increase the number of experts in STEM fields to drive innovation and to keep the country competitive in the global economy. In India, 600 million people are under 25 years of age. A vast majority of this population lives in challenging conditions such as low quality of education (primary through tertiary), socio-economic backwardness, inadequate skill education, etc. To overcome this, the existing educational institutions must include the latest developments in STEM in their curricula in a holistic manner, with students' employment opportunities and social development. Primary data were collected from 366 students pursuing higher

education in STEM areas - BSc, MSc, and BTech/MTech – at various universities/colleges in Kerala. The findings of the paper shed light on the relationship between STEM education, innovation, creativity, scientific research, and employment.

Keywords: Career Pathways, Study Provisions and Study Conditions, Academic Information, Curriculum Issues, Human Capital, STEM pipeline

1. Introduction

"STEM pipeline" refers to the educational and career pathway that individuals can follow to enter and advance in the fields of Science, Technology, Engineering, and Mathematics (STEM). The pipeline is a metaphorical representation of the various stages and transitions that a person goes through to become a successful professional in a STEM-related field. The STEM pipeline typically begins with K-12 education, where students learn the foundational concepts and skills that are essential for STEM fields. This includes subjects such as mathematics, physics, chemistry, biology, and computer science. After completing high school, students can pursue undergraduate and graduate degrees in a STEM discipline at a college or university. During this phase of the pipeline, they gain more in-depth knowledge and specialized skills in their chosen field. After completing their education, individuals can enter the workforce and pursue a variety of career paths in STEM fields (Toma 2020). These can include jobs in research and development, engineering, information technology, healthcare, and many others. the STEM pipeline represents the journey that individuals take to develop the knowledge, skills, and experiences necessary to succeed in STEM-related careers. It is an ongoing process that requires continuous learning and adaptation to keep pace with the rapidly evolving world of science and technology.

Worldwide, the countries in the global economy have made serious efforts to strengthen the pipeline of students into STEM fields. A need to foster STEM education to maintain a steady workforce flow to keep pace with the scientific developments based on artificial intelligence, data analytics, and other knowledge-intensive fields of the modern world. Hence India now faces an emergent concern for the growing demand for an educated workforce with the technical skills processing science and mathematics knowledge.

Hence the current paper focuses on the different factors of higher education in STEM disciplines and how they impact the quality of students who pursue education in this wide setting. The numerous aspects and critical variables that

affect persons seeking STEM education in various colleges in the state of Kerala are discussed in this paper.

The paper addresses the following research questions: What role do institutions promote higher education in STEM fields? What social, demographic, and geographic variables influence students' decision to pursue higher education in STEM fields? What are the study provisions and study conditions existing in the higher education institutions for STEM graduates? What are the aspirations regarding the opportunities in the STEM related fields as far as the STEM graduates are concerned? What is the level of participation in scholarly activities by STEM graduates? What are the sources of Academic information for the STEM graduates? How do the STEM graduates perceive the opportunities or challenges of the career? What are the issues with the curricula and General study process that exist in the higher education institutions for the STEM graduates?

Following the introduction section, a brief review and methodology are presented. A detailed results and discussion section is followed by a brief conclusion of the paper.

2. Review of literature

Education increases people's engagement in economically productive activities and helps them become more effective by providing them with the necessary skills to participate in society's day-to-day activities fully. It enables workers to benefit from technological advancements, increasing their productivity and profits. Education was once seen to be the cure for social mobility, acquiring knowledge was the primary goal. But, over time, people's attitudes about education shifted, and the pursuit of employment took precedence over knowledge acquisition.

Becker's (1962) human capital theory examines how the allocation of schooling time or resources impacts workers' future production through their skill level. Education is a crucial component of economic development, and intergenerational knowledge spillovers are critical. The relevance of the links between education and work has been highlighted in several studies.

In his study, Arcidiacono (2005) found that the quality of college influences an individual's expected earnings attended, the major pursued, the individual's measured math and verbal abilities, the individual's expected grades based on the school and major pursued, and other relevant individual characteristics such as gender. It is clearly recognized that education has a causal influence on people's transitions from work to unemployment.

Aside from that, education helps jobless workers re-enter the workforce (Riddell and Song 2011). Individuals' present and anticipated wages are

determined by their educational backgrounds. Individuals like work more than others, according to their respective abilities and other unique traits, according to studies. Adapting to the changes brought about by modern globalization is a crucial challenge for higher education. The role of engineering in society is evolving due to globalization, changing socio-demographics, and technological advancements. STEM professionals are being pushed to obtain the skills to succeed in an increasingly global market. This correlates to shifting demands in university-level abilities, notably in STEM sectors (Yamada 2017).

Xie et al. (2015) talk about the contextual variables that influence STEM education on school-specific characteristics. Other possible contextual variables, such as local labor market features or closeness to science-focused industries, are little understood. Schools with enough resources provide a more diverse range of math and science courses and better access to resources. Student learning and academic success benefit from having access to qualified and experienced math and science professors. High levels of interest in and love for science are similarly linked to high-quality instructors. Cross-school disparities in family and community SES are reflected in the quality of scientific laboratories.

Craft et al. (2017) noted that the US economy's policy to expand STEM Ph.D. employment has concentrated on supply rather than demand. According to the findings, the future supply of STEM PhDs will be primarily influenced by the availability of tenured academic posts. It implies that a demand-side strategy, driven by full-time tenure-track academic job vacancies, maybe a more successful policy. One of the main challenges for STEM education is the infrastructure and, in turn, the funds needed to create quality infrastructure. That is the main reason why the corporate world needs to collaborate with the world of education. The cost of doing quality research has indeed exploded over the decades. And for cutting-edge innovations to happen, the facilities need to be cutting edge.

According to Pantic (2007), the United States has to develop a STEM pipeline that runs from pre-kindergarten to college and then into the industry. International competition, he claims, exacerbates the gap between supply and demand for STEM personnel. To lead the global knowledge-based economy, the country must invest in K-12 science and math education, mentoring initiatives, and retention programs. According to research conducted by the National Science Foundation (NSF), three variables contribute to developing a solid pipeline for STEM employment. Early exposure to STEM fields through role models and mentors, good K-12 math and science preparation, and effective college retention programs are just a few of them.

3. Methodology

To discover answers to the questions, 366 students pursuing higher education in STEM areas - BSc, MSc, and BTech/MTech – at various universities/colleges in Kerala were interviewed using stratified random sample techniques. A detailed interview schedule was prepared to collect primary data. The data are analyzed using statistical tools such as descriptive statistics, chi-square, ANOVA and factor analysis.

4. Results and discussions

India needs to increase the number of experts in STEM fields to drive innovation and to keep the country competitive in the global economy. In India, 600 million people are under 25 years of age. A vast majority of this population lives in challenging conditions such as low quality of education (primary through tertiary), socio-economic backwardness, inadequate skill education, etc. To overcome this, the existing educational institutions must include the latest developments in STEM in their curricula in a holistic manner, with students' employment opportunities and social development.

Keeping the background in mind, the study focussed on how the students who are in the STEM pipeline responded to the challenges faced in the field. The results of the study are provided in the following sub-sections.

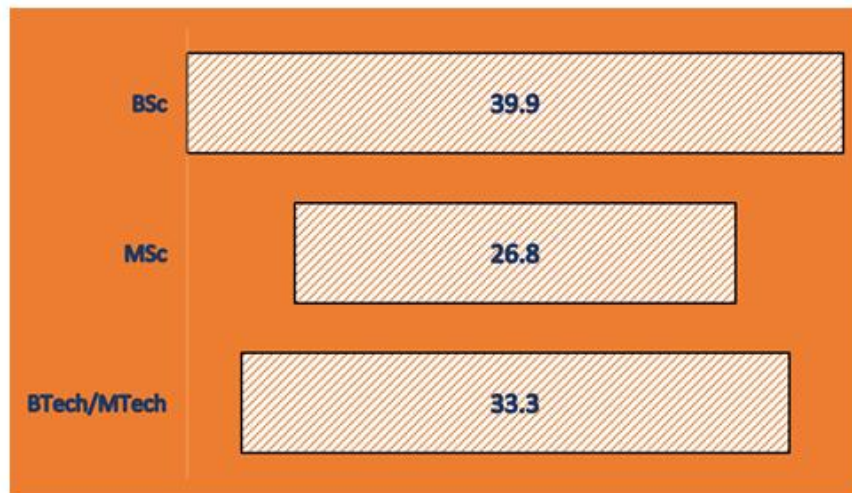
4.1 Profile of respondents

For the present study, 366 undergraduate and postgraduate students who pursue higher education were interviewed based on a proportional sampling technique. These students either belong to the major universities - University of Kerala (UoK), Cochin University of Science and Technology (CUSAT), University of Calicut (UoC), Mahatma Gandhi University (MGU), Kannur University (KU), and APJ Abdul Kalam Technological University (KTU). A good share of the students is selected from the major colleges affiliated to these universities who pursue either their BSc/MSc degree or BTech/MTech degrees.

4.1.1 STEM subjects opted for

The students studying in different institutions were divided into three significant fields to analyze the primary data. The data show that the highest share of respondents (n=146) is from BSc, constituting around 39.9 per cent of the total students. The second-highest number of respondents is from BTech/MTech subjects (122), with a share of about 33.3 per cent (Figure 1). The least number of respondents (98) is from MSc, who constitute only 26.8 percent.

Figure 1: Profile of respondents



Source: Field Survey, 2019-2020

The subjects coming under BTech/MTech are Applied Electronics and Instrumentation Engineering, Chemical Engineering, Civil Engineering, Computer Science and Engineering, Computer Software, Electrical Engineering, Electrical and Electronics Engineering, Electronics and Communication Engineering, Electronics and Media Technology, Geotechnical Engineering, Information Technology, Mechanical Engineering, and Structural Engineering and Construction.

For BSc and MSc, subjects found to be studied by the students are Bio-Technology, Biochemistry & Molecular Chemistry, Biodiversity Conservation, Botany, Chemistry, Computational Biology, Computer Applications, Computer Science, Data Analytics, Earth Science, Electronics, Geology, Machine Design, Mathematics, Genetic and Plant Breeding, Statistics, Optoelectronics, Physics, Statistics with Data Analytics, Statistics with Specialisation in Data Analytics and Zoology.

4.1.2 Type of institution opted for

Students who opt for different Programs have varied options for the type of institutions they choose to study. There is a plethora of institutions that cater to the varied needs of the students in the state of Kerala. Many of them are in the government sector, some are in the aided sector, and yet another type of institution works in self-financing mode.

The students are almost equally distributed among the different types of institutions, with 36.6 per cent in government, 33.6 per cent in the aided sector, and 29.8 per cent in self-financing institutions. This demonstrates that the

quality of education offered by both government and aided schools is high and that it has not deterred people from achieving success later in life.

The chi-square results show an association among the programs and the type of institutions under the study as the p-value is less than .05.

Figure 2 shows that the population's access to the institutions, whether public or aided or private, was equal. None of the sectors (government or self-financing) hesitated to build institutions wherever they were required, even if it was in a distant location. It is to be noted that 67.3 per cent of those who do PG in STEM areas depend on the government sector. The facilities are more in many of the institutions, primarily in the University teaching departments. On the other hand, for those who do BTech, a good majority (43.4 per cent) is depending on self-financing institutions for their studies. On the other hand, for the UG in STEM areas, the aided sector is playing a great role with colleges opened in almost all parts of the state which helps the students to have access to higher education.

Figure 2: Type of institution opted by the students vis-à-vis programs



Source: Field Survey, 2019-2020

4.2 Demographic characteristics of students

While exploring the data a little deeper, some interesting facts emerge. It is generally observed that within the different universities/colleges, the composition of students who pursue their studies in diverse areas differs widely. The demographic characteristics of students give an idea of the background of the students who opted to study in the STEM fields.

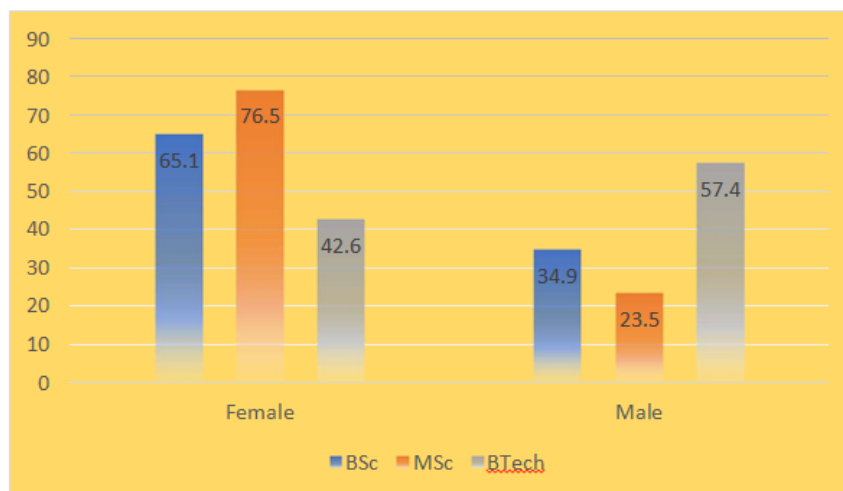
4.2.1 Gender

Even though the representation of females varies across the institutions, one can observe prominent domination of females in all the programs under consideration. Of the total students, 60.7 per cent are females, and the rest are males. When it comes to gender differences, it is worth noting that there is not much of a difference between the two. This paints a very clear picture of women in Kerala participating in higher education on par with males. The chi-square results show a significant association among the programs the students choose based on gender.

Although the participation of females is generally higher, the most significant representation of women is found in the MSc program (76.5 per cent), which is impressive. One of the reasons behind this phenomenon is that a greater number of women prefer to go for PG programs. The institutions usually give admission based on marks which the girl students generally fare well. This, in turn, enhances the accessibility of women to the PG programs (Figure 2).

Another major factor is that there is no gender discrimination in education, and so it indicates social empowerment. The participation of women in BTech/MTech is comparatively low. It is to be noted that gender participation is not even throughout the different programs. The involvement of male students is less than 40 percent in most of the programs except the BTech/MTech programs. It is found to be almost the same across all the fields of study (Figure 3).

Figure 3: Gender participation in higher education



Source: Field survey, 2019-2020

4.2.2 Age

Age is the most important demographic characteristic which affects the educational activities of a person. The age determines how one conceptualizes the problems around them in the world, collects information, organizes the information and experiences, and acts upon it. Thus, it all depends on age. When one looks at the demographic characteristics of the students, from the point of view of age, it is found that the majority of the students are found to be in the age interval between 18 and 25.

Table 1: Age of the students

Program	Min	Max	Range	Medin	Mean	SD	F (P-Value)
BSc	18	25	7	21	20.98	1.791	43.908 (.000)
MSc	21	30	9	23	22.97	1.495	
BTech/ MTech	18	30	12	23	22.34	1.785	
Total	18	30	12	22	21.97	1.906	

Source: Computed

When it comes to the field of study, the highest mean age (22.97) is to be found with the PG, and the lowest could be seen with the UG programs (20.98). While comparing among the programs, the MSc (Table 1) has the most significant number in the highest age group. The BSc has the most important number of students in the lowest age group of 18-25. The SD for BSc is found to be less compared to other fields of study, which shows that the variability is less when it is compared to the different areas of study. After graduation, some students try to find some odd jobs or engage in some temporary assignments. This makes them enter the field of postgraduate late, which is evident from the high proportion of PG students in the higher age groups. The ANOVA test proves a variability within the field of study with the p-value is less than 0.05.

4.3 Social characteristics of respondents

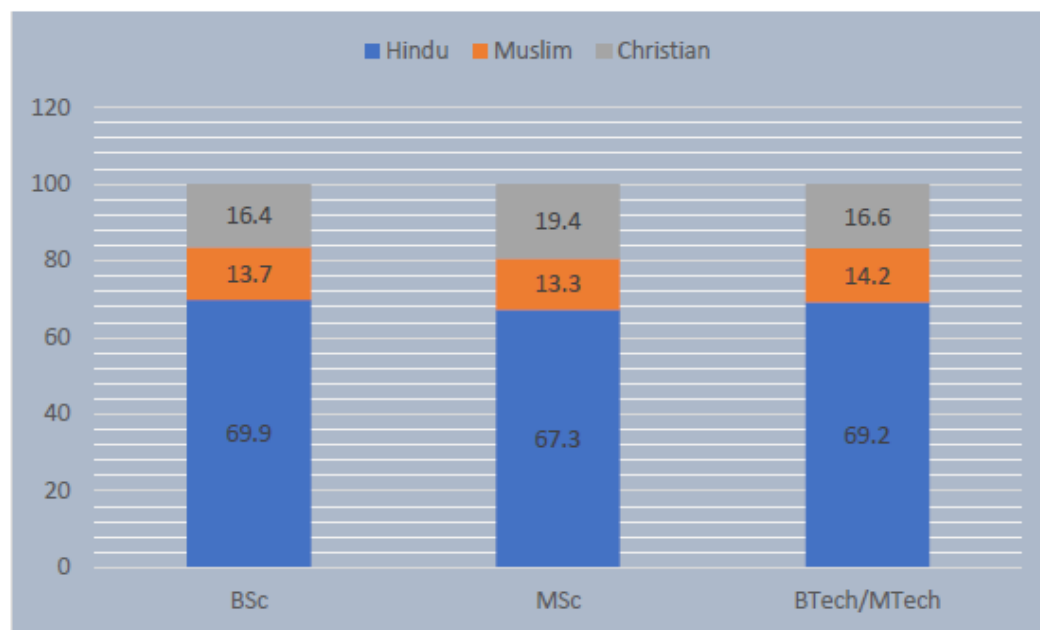
While looking from the societal perspective, the students' religious and community background is one of the most important factors determining their participation in higher education.

4.3.1 Religion

The primary survey results show that the students who identified themselves as belonging to the Hindu Community are found to be 69 per cent. This participation is very high compared to other religions, and it is natural in the socio-cultural context of Indian society. When the composition of the sample is analyzed, it is seen that 17.3 per cent are Christians.

The concentration of Muslims in the sample is far less at 13.7 per cent. Even though there are many affirmative actions taken up, the current Muslim population in the higher education sector, especially in the STEM-related areas, is still low. Using the chi-square Test, a study of the religious characteristics of pupils was done. The test was used to see if there was a link between the program of study and religion. We accept the null hypothesis that both variables are independent since the p-value (0.98) is higher than the significant threshold (0.05). As a result, it demonstrates there is no link between programs and students' religious backgrounds.

Figure 4: Religion of the respondents



Source: Field Survey, 2019-2020

Figure 4 shows that minority populations such as Christians and Muslims are underrepresented in higher education. The findings support previous findings that minority populations participate in society's possibilities lower than other groups. This must also be considered from the perspective of the minority community's far greater representation in Kerala's social environment. The causes for the low participation of minorities in higher education must be thoroughly investigated. The majority of the minority population/social community's and economic backwardness is seen as a critical contributor to the current situation.

4.3.2 Community

The students belong to several social categories, including Scheduled Castes (SC), Scheduled Tribes (ST), Other Backward Classes (OBC), Other Eligible Communities (OEC), and the General category. When examining the representation of social groupings, the OBC category has the most significant

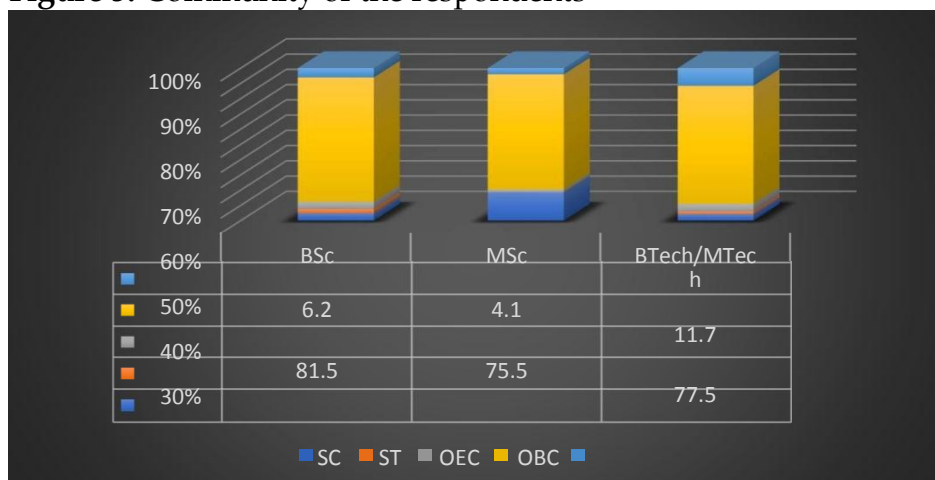
proportion (78.6 per cent). With 8.2 per cent, students in the SC category come in second.

With 1.6 and 4.1, the ST and OEC categories have the smallest number of students in the sample. The Three socially backward and socially disadvantaged social groupings (SC, ST, and OEC) account for roughly 15 per cent of the total respondents. While using the chi-square test, it is shown that there is a significant relationship between the students' community and the programs. In the chi-square test, the p-value (0.001) is less than the significant level (0.05), which in turn has not accepted the null hypothesis, and thus both the variables are independent.

On the one hand, most of the respondents are from the OBC and general populations, which reflect society's political and social power structure. The OBC and general groups own many management schools and colleges in various regions of the state. As a result, students from different groups in Kerala can graduate and take advantage of the institutions' chances. At the same time, government-enforced reservation policies aided disadvantaged groups in gaining access to additional possibilities in the competitive world of education.

Figure 5 gives a picture of the same as the representation of OBC is relatively high across the different programs considered for the study. The representation of SC students in the MSc program is more remarkable with 18 per cent. While analyzing the community characteristics of students, more concentration of OEC category is reported in BSc compared to other programs. The representation of SC is phenomenal in the MSc, but the picture is less in BTech/MTech. The representation of ST is nil in MSc, which again causes concern about the poor educational attainment of the community in the state. It is also noted that the representation of OBC is almost even across the programs.

Figure 5: Community of the respondents



Source: Field Survey, 2019-2020

4.4 Merits during the study

Financial assistance based on performance, achievement, or other factors boosts the students who pursue STEM education. The funder makes no particular requirement that the funds be used for educational purposes. It is only to encourage the student in their studies. Departments and schools, for example, recognize pupils during end-of-year award ceremonies. At that moment, certificates are usually handed over to pupils.

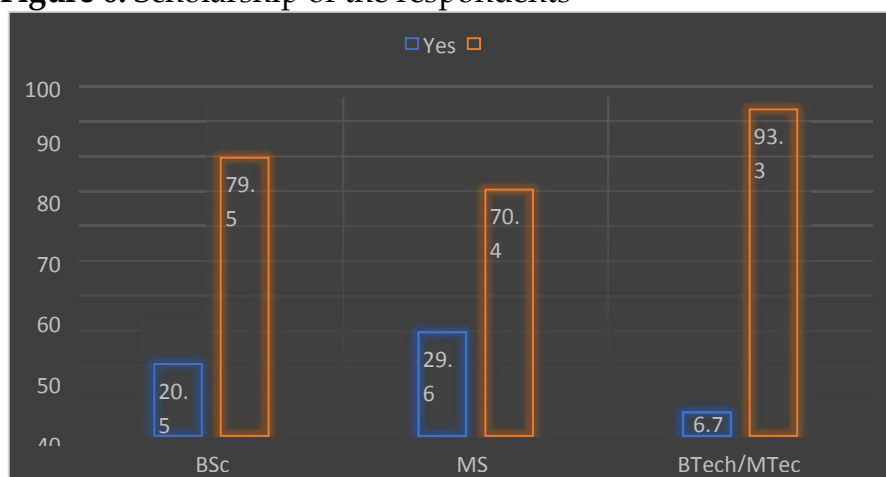
4.4.1 Scholarship

A scholarship is a monetary reward given to students who wish to continue their education at a college, university, or other intellectual institution. Approximately 18 per cent of the students who responded to the study admit that they have received some type of scholarship.

Some of the scholarships the students avail belongs to E Grantz, Higher Education Scholarship, Indira Gandhi Scholarship, INSPIRE, KPCR, MCM scholarship, University Merit Scholarship, Moulana Azad Muslim scholarship, OBC post metric scholarship, Prathibha scholarship, Suvarna Jubilee, SEBC, Summonathi, Vidya Samunnathi, XSA scholarship, etc. The chi-square results show that there is an association between the programs and the responses.

Of the total respondents, those who have not received any scholarship during their period of study form 81.6 per cent. The proportion of respondents based on receipt of scholarship is given in Figure 6. Approximately 30 per cent of the students who are currently studying in MSc Program could receive some kind of scholarship, while 6.7 per cent of the students who pursue the BTech program can avail scholarships.

Figure 6: Scholarship of the respondents



Source: Field Survey, 2019-2020

4.5 Mobility

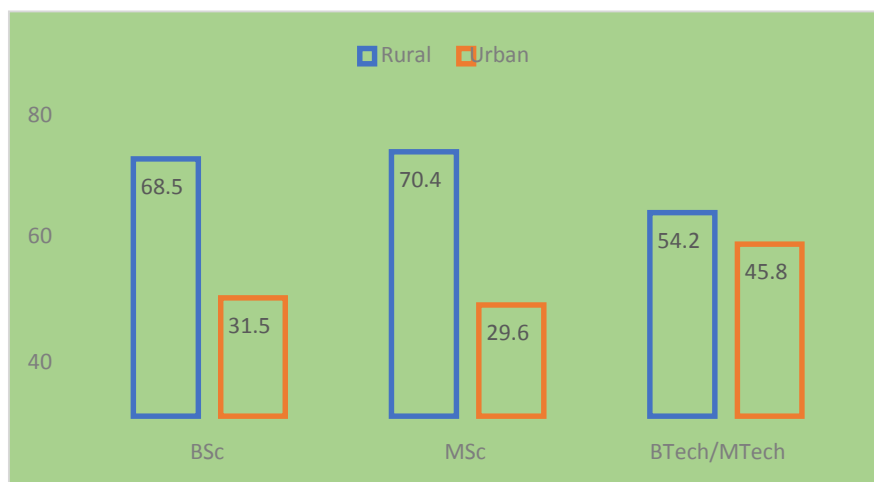
The notion of mobility in education refers to people's social mobility from one social stratum to another due to the development brought about by education in their lives. However, this part focuses solely on people's physical mobility, fuelled by a desire for higher education and access to prestigious universities. Access to education was examined from the supplier's perspective, whether the government or the private sector gave it. In contrast, mobility was discussed from the perspective of the individual who used the service.

4.5.1 Place of residence

A 64.3 per cent of the total sample hail from rural areas. This demonstrates that Kerala's rural districts have a distribution of higher education institutions that is comparable to that of metropolitan areas. Hence it is found that the distribution of educational institutions (universities and colleges) in Kerala is well established, whether in rural or urban areas. The chi-square results show that the association between place of residence and the programs has some association.

Figure 7 show that approximately 70 per cent of the BSc and MSc students hail from rural areas, while 54 per cent of BTech students are from rural regions.

Figure 7: Place of Residence vis-à-vis programs



Source: Field Survey, 2019-2020

4.5.2 Distance from home

Yet another indicator used to measure the mobility of the students is that of the distance from home to the institution. The highest mean is found to be with MSc programs (105.67 km) where the students have to travel for more distance to find a program of their choice. The students who pursue the BTech/MTech degrees have the lowest mean (31.51 km) with the lowest standard deviation (67.647 km). The median distance is also low for BTech/MTech students (15

km) followed by the BSc students (16 km). The ANOVA results also show that there is variation among the different programs.

Table 2: Distance from home (in Km) to the institution

Program	Min	Max	Range	Median	Mean	SD	F (P-Value)
BSc	2	500	498	16.00	44.31	95.503	16.947 (.000)
MSc	1	540	540	35.50	105.67	131.830	
BTech/ MTech	1	546	545	15.00	31.51	67.647	
Total	1	546	546	18.00	56.61	103.472	

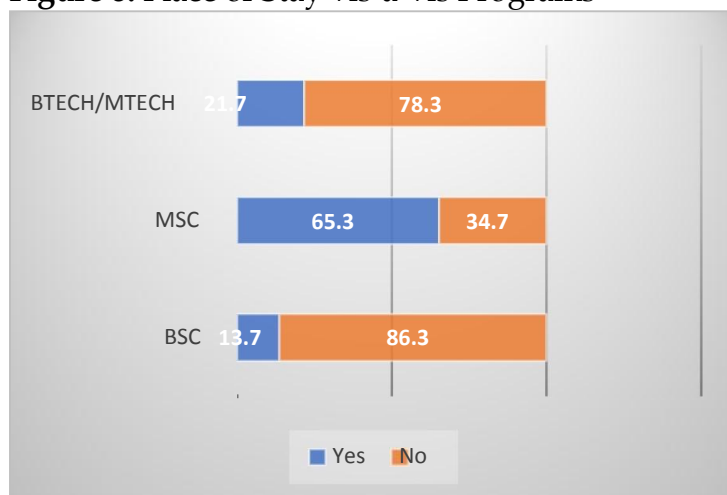
Source: Computed

4.5.3 Place of stay

The place of stay during their studies plays a significant role in pursuing the same. Approximately 70 per cent of the total respondents stayed at home while the rest stayed in the College Hostel, University Hostel, Private Hostel, and used Paying Guest facility. The chi-square test shows that there is an association between the programs and the responses.

The analysis based on the program-wise data is presented in Figure 8. Around 65 per cent of the total students who pursue their MSc programs depend on the stay outside their homes as they are doing their studies in far-off places. The least number of students who rely on hostels is in the BSc program (13.7 per cent), which makes clear that they have their institutions near their homes.

Figure 8: Place of Stay vis-a-vis Programs



Source: Field Survey, 2019-2020

4.6 Study provision and study conditions in STEM higher education

Excellent conditions both inside and outside lecture classrooms are most important for a student. The current section gives a detailed analysis of how the perceptions towards the existing study provisions and study conditions in STEM higher education from the point of view of the students. The descriptive statistics presented in Table 3 prove that the rank for all the statements is pretty high, i.e., the mean value is less than 2.5 the overall feeling of the students regarding the courses offered, programs they have chosen, quality of the study materials, evaluation methods, extra-curricular STEM activities, etc., provided to them.

Table 3: Study provision and study conditions: Descriptive statistics

Study provision and Study Conditions	Very good	Good	Not Good	Bad	Very Bad	Mean	S D
Course content	133 (36.3)	214 (58.5)	14 (3.8)	5 (1.4)	0 (0.0)	1.70	.607
Variety of courses offered	138 (37.7)	181 (49.5)	36 (9.8)	11 (3.0)	0 (0.0)	1.78	.739
Design of degree program	106 (29.0)	195 (53.3)	41 (11.2)	23 (6.3)	1 (0.3)	1.96	.823
Opportunity to choose courses and areas of specialisation	124 (33.9)	173 (43.3)	43 (11.7)	22 (6.0)	4 (1.1)	1.93	.890
Practical emphasis of teaching and learning	108 (29.5)	168 (45.9)	52 (14.2)	33 (9.0)	5 (1.4)	2.07	.958
Quality of technical equipment	100 (27.3)	180 (49.2)	42 (11.5)	38 (10.4)	6 (1.6)	2.10	.971
Research emphasis of teaching and learning	87 (23.8)	175 (47.8)	60 (16.4)	30 (8.2)	14 (3.8)	2.20	1.017
Testing/grading system	77 (21.0)	177 (48.4)	58 (15.8)	41 (11.2)	13 (3.6)	2.34	1.533
Provision of work placements and other work experience	88 (24.0)	146 (39.9)	71 (19.4)	40 (10.9)	21 (5.7)	2.36	1.254
Equipment and stocking of libraries	112 (30.6)	178 (48.6)	43 (11.7)	22 (6.0)	11 (3.0)	2.02	.968
Chances to participate in research projects	90 (24.6)	144 (39.3)	72 (19.7)	43 (11.7)	17 (4.6)	2.33	1.108
Teaching quality	122 (33.3)	187 (51.1)	27 (7.4)	22 (6.0)	8 (2.2)	1.93	.917
Supply of teaching material	107 (29.2)	202 (55.2)	31 (8.5)	24 (6.6)	2 (0.5)	1.94	.829
Academic advice offered in general	101 (27.6)	197 (53.8)	39 (10.7)	24 (6.6)	5 (1.4)	2.00	.877
Assistance/advice for your final examination	104 (28.4)	199 (54.4)	32 (8.7)	27 (7.4)	4 (1.1)	1.98	.876

Opportunity of out-of-class contacts with teaching staff	102 (27.9)	184 (50.3)	29 (7.9)	41 (11.2)	10 (2.7)	2.11	1.021
Contacts with fellow students	131 (35.8)	150 (41.0)	38 (10.4)	17 (4.6)	30 (8.2)	2.08	1.176
Chance for students to have an impact on university policies	73 (19.9)	124 (33.9)	92 (25.1)	39 (10.7)	38 (10.4)	2.58	1.218

Source: Computed

For identifying the main factors determining study provisions and study conditions, factor analysis was applied to the response provided by the respondents, as shown in Table 4. Factor analysis is usually conducted for analyzing correlations between variables and reducing them into fewer factors to explain the original data more economically. Two stages of factor analysis are performed here, namely the Factor Extraction process, which decides upon the number of factors to be extracted from data. The second stage of Factor analysis employed is the Rotation of Principal components, whereby the extracted factors are titled.

A Rotated Component Matrix is used in this stage to analyze and interpret the factors. The factor matrix represents the factor loadings of each variable on the extracted factors. The high loading factors are identified and titled. Values close to one represent high loadings, and those close to zero represents low loadings. The Kaiser-Meyer-Olkin Measure of sampling adequacy and Bartlett's Test of Sphericity have been applied to test whether the relationship among the variables is significant or not.

Higher values of the Kaiser-Meyer-Olkin (KMO) test of sampling frequency (.905) indicate that the correlation between the pairs of variables is explained by other variables, and thus the factor analysis is considered to be appropriate for this model. The Bartlett's Test of Sphericity for women entrepreneurship intention, approximate Chi-square 3213.400 with degrees of freedom 153 and $P < 0.05$, show patterned relationships between the items, and the correlation matrix measures significantly make the factor analysis appropriate.

Table 4: Study provision and study conditions: Factor analysis

KMO and Bartlett's Test				
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.				.905
Bartlett's Test of Sphericity	Approx. Chi-Square			3213.400
	df			153
	Sig.			.000
Rotated Component Matrix ^a				
Statements	Factors	Component		
		1	2	3
Course content	Course specific	.685	.164	.161
Variety of courses offered		.745	.219	.108
Design of degree program		.801	.172	.090
Opportunity to choose courses and areas of specialisation		.732	.199	.116
Practical emphasis of teaching and learning		.646	.422	.118
Quality of technical equipment		.556	.317	.361
Research emphasis of teaching and learning		.428	.407	.452
Testing/grading system		.400	.088	.413
Teaching quality	Teaching and evaluation	.177	.658	.327
Supply of teaching material		.194	.764	.222
Academic advice offered in general		.281	.763	.155
Assistance/advice for your final examination		.299	.768	.153
Opportunity of out-of-class contacts with teaching staff		.179	.627	.245
Provision of work placements and other work experience	Extra-curricular activities	.345	.335	.464
Equipment and stocking of libraries		.174	.228	.710
Chances to participate in research projects		.259	.405	.522
Contacts with fellow students		-.035	.123	.826
Chance for students to have an impact on university policies		.161	.248	.765
Eigenvalues	7.617	1.694	1.158	
Per cent of total variance explained	42.316	9.410	6.434	
Cumulative per cent of the variance explained	42.316	51.727	58.160	
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.				
a. Rotation converged in 15 iterations.				

Source: Computed

Eighteen factors determining study provisions and study conditions were identified. The respondents were asked to express their level of opinion on the influence of each of these factors on a five-point Likert scale. Factor loadings in the rotated component matrix show that the first factor strongly loads study provisions and study conditions on eight items. The highest loading is .801 for

the Design of the degree program, and the minimum loading 0.4 for the Testing/grading system. The second factor in study provisions and study conditions loads on three variables, the maximum loading for Assistance/advice for your final examination is .768, and the minimum loading for the Opportunity of out-of-class contacts with teaching staff is .627.

The factor analysis extracted three components significant to study provisions and study conditions, namely; Course-specific, Teaching and evaluation, and Extra-curricular activities. These factors account for about 58.160 per cent of the variance in the data. Course-specific factor comprises of nine items. The Eigenvalue for the same factor is 7.617, which indicates that this factor contains very high information than the other factors. This factor provides the maximum insights of elements influencing study provisions and study conditions in the study area. The second factor, namely; Teaching and evaluation for about 9.410 per cent of the variance. The Eigenvalue for this factor is 1.694. The last factor, namely; Extra-curricular activities for about 6.434 per cent of the variance. The Eigenvalue for this factor is 1.158.

4.7 Opportunities in the STEM-related fields

The students are anxious about finding a job after their studies. Therefore, an analysis was done to understand the opportunities in different places. In general, the students feel that it is difficult to obtain a job/career. A very few students think that it is easy to get a job in the STEM-related fields. The least mean value (2.61) is obtained by the statement “To find a career opportunity in Kerala is” problematic. A considerable majority have a pessimistic view that they cannot find a job inside their state (Table 5). On the other hand, the students feel that they may get better opportunities if they move out to other places.

Table 5: Opportunities in the STEM-related fields: Descriptive Statistics

Opportunities	Very difficult	Difficult	Don't Know	Easy	Very Easy	Mean	S D
To find an opening in my discipline is	40 (10.9)	130 (35.5)	62 (16.9)	123 (33.6)	11 (3.0)	2.82	1.105
To find a career opportunity in Kerala is	55 (15.0)	150 (41.0)	48 (13.1)	109 (29.8)	4 (1.1)	2.61	1.097
To find a career opportunity in India is	36 (9.8)	129 (35.2)	53 (14.5)	140 (38.3)	8 (2.2)	2.88	1.097
To find a career opportunity abroad is	44 (12.0)	77 (21.0)	95 (26.0)	123 (33.6)	27 (7.4)	3.04	1.157
For women, getting a career opportunity is	37 (10.1)	110 (30.1)	82 (22.4)	116 (31.7)	21 (5.7)	2.93	1.118
For men, getting a career opportunity is	25 (6.8)	96 (26.2)	78 (21.3)	139 (38.0)	28 (7.7)	3.13	1.098

Source: Computed

To find out the opinion on opportunities in STEM fields of the students in higher education, six attributes were identified. The Rotated component matrix for the variables relating to opportunities is given in Table 6. The KMO Test of Sampling Adequacy (.850) indicates that the correlation between pairs of variables explained by other variables and factor analysis is appropriate to this model. Bartlett's Test of Sphericity for push factors with Chi-square = 972.059 and degrees of freedom 15 with $P < 0.05$ shows a patterned relationship between the items.

Table 6: Opportunities in the STEM-related fields: Factor analysis

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.850
Bartlett's Test of Sphericity	Approx.Chi-Square	972.059
	df	15
	Sig.	.000
Rotated Component Matrix ^a		
Statements	Component	
	1	
To find an opening in my discipline is	.750	
To find a career opportunity in Kerala is	.770	
To find a career opportunity in India is	.842	
To find a career opportunity abroad is	.666	
For women, getting a career opportunity is	.770	
For men, getting a career opportunity is	.833	
Eigenvalues	3.594	
Per cent of total variance explained	59.905	
Cumulative per cent of the variance explained	59.905	
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.		
a. Rotation converged in 15 iterations.		

Source: Computed

Factor loading in the rotated component matrix shows that the first factor strongly loads push motivators on one item. The highest loading is .842, and the minimum loading .666. One factor is significant to opportunities. This factor account for about 59.905 per cent of the variance in the data. The eigenvalue for the first-factor uncertainty is 3.594, which shows that this factor has a very significant influence on opportunities compared to other factors.

4.8 Participation in scholarly activities

Participation in scholarly activities helps the students to update with the latest developments in the STEM fields. The activities such as attended workshop with school students, attended workshop with a public group, attended drop-in activities, and attended public debate or discussion got a mean value less than two which gives an impression that these activities are less attended by the students participated in the survey. On the other hand, the activity on 'Attended Lecture/Talk to college students' has been participated by a majority of the students, and its mean value is more significant than three (Table 7).

Table 7: Participation in scholarly activities: Descriptive statistics

Scholarly activities	Never	Once	2-3 times	4-5 times	More than 5 times	Mean	S D
Attended Lecture/Talk to college students	97 (26.5)	50 (13.7)	63 (17.2)	31 (8.5)	125 (34.2)	3.10	1.626
Attended Lecture/Talk to a public group	159 (43.4)	61 (16.7)	70 (19.1)	39 (10.7)	37 (10.1)	2.27	1.376
Attended Workshop with school students	218 (59.6)	70 (19.1)	45 (12.3)	16 (4.4)	17 (4.6)	1.75	1.120
Attended Workshop with a public group	226 (61.7)	56 (15.3)	50 (13.7)	18 (4.9)	16 (4.4)	1.75	1.133
Attended Drop-in activities (e.g., at a science festival or similar public event)	183 (50.0)	78 (21.3)	60 (16.4)	28 (7.7)	17 (4.6)	1.96	1.179
Attended Public	226 (61.7)	66 (18.0)	43 (11.7)	19 (5.2)	12 (3.3)	1.70	1.073

Source: Computed

To find out the factors on the participation of scholarly activities, six attributes that can influence the same were identified. The Rotated component matrix for the variables relating to the scholarly activities is given in Table 8. Factor loadings in the rotated component matrix show that the first factor strongly loads pull motivators on six-factor items. The highest loading is .839, and the minimum loading .623.

Table 8: Participation in scholarly activities: Factor analysis

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.795
Bartlett's Test of Sphericity	Approx. Chi-Square	1024.622
	df	15
	Sig.	.000
Rotated Component Matrix ^a		
Statements	Component	
	1	
Attended Lecture/Talk to college students	.623	
Attended Lecture/Talk to a public group	.800	
Attended Workshop with school students	.743	
Attended Workshop with a public group	.839	
Attended Drop-in activities (e.g., at a science festival or similar public event)	.816	
Attended Public debate or discussion	.754	
Eigenvalues	3.519	
Per cent of total variance explained	58.642	
Cumulative per cent of the variance explained	58.642	
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.		
a. Rotation converged in 15 iterations.		

Source: Computed

The high value of KMO Test of Sampling Adequacy (.795) indicates that the correlation between pairs of variables explained by other variables and factor analysis is appropriate to this model. The Bartlett's Test of Sphericity for push factors with Chi-square = 1024.622 and degrees of freedom 15 with $P < 0.05$ shows a patterned relationship between the items.

Only one participation in scholarly activities is extracted out of the six variables. This factor account for about 58.642 per cent of the variance in the data. The Eigenvalue for the factor is 3.519, which shows that this factor has a powerful influence on the analysis.

4.9 Academic information

The current section is on the ways in which the information regarding academic activities is gained by the different respondents. The lowest mean value (Table 9) is found to be seen in the case of the statement 'Personal contact' (2.22), and the highest mean value is for the 'National Conference' (3.61).

Table 9: Academic information pathways: Descriptive statistics

Information Pathways	At least once a week	1-5 times a term	1-2 times a year	Less than once a year	Never	Mean	SD
Personal contact (i.e., meeting an advisor, other teachers or experts)	149 (40.7)	102 (27.9)	37 (10.1)	43 (11.7)	35 (9.6)	2.22	1.341
International Conference	19 (5.2)	52 (14.2)	91 (24.9)	94 (25.7)	110 (30.1)	3.61	1.199
National Conference	16 (4.4)	56 (15.3)	106 (29.0)	80 (21.9)	108 (29.5)	3.57	1.186
Printed publicity	34 (9.3)	68 (18.6)	70 (19.1)	74 (20.2)	120 (32.8)	3.49	1.356
Emails	94 (25.7)	87 (23.8)	64 (17.5)	46 (12.6)	75 (20.5)	2.78	1.473

Source: Computed

To find out the information pathways, five attributes were identified. The Rotated component matrix for the variables relating to information pathways is given in Table 10. The KMO Test of Sampling Adequacy (.771) indicates that the correlation between pairs of variables explained by other variables and factor analysis is appropriate to this model. Bartlett's Test of Sphericity with Chi-square = 923.716 and degrees of freedom 10 with $P < 0.05$ shows a patterned relationship between the items.

Table 10: Academic information pathways: Factor analysis

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.771
Bartlett's Test of Sphericity	Approx. Chi-Square	923.716
	df	10
	Sig.	.000
Rotated Component Matrix ^a		
Statements	Component	
	1	
Personal contact (i.e., meeting an advisor, other teachers or experts)	.414	
International Conference	.877	
National Conference	.918	
Printed publicity	.855	
Emails	.681	
Eigenvalues	2.979	
Per cent of total variance explained	59.576	
Cumulative per cent of the variance explained	59.576	
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.		
a. Rotation converged in 15 iterations.		

Source: Computed

Factor loadings in the rotated component matrix show that the only factor strongly loads information pathways on five-factor items. The highest loading is .918, and the minimum loading is .414. The only factor significant to information pathways was extracted out of the five variables. These factors account for about 59.576 per cent of the variance in the data. The eigenvalue for the element is 2.979, which shows that this factor has a very significant influence on information pathways.

4.10 Opportunities/challenges about the career

A set of variables were used to bring out the different aspects of Opportunities/Challenges about the career. Table 11 gives a vivid picture of the same various variables identified. The statement 'Scientists make a meaningful difference in the world receives the highest mean of 4.29, and the statement 'It is boring to work as a scientist throughout life' gets the least mean of 3.34.

Table 11: Opportunities/Challenges about the career: Descriptive statistics

Opportunities/Challenges about the career	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree	Mean	SD
I would like to have a career in my area of STEM.	7 (1.9)	21 (5.7)	72 (19.7)	132 (36.1)	134 (36.6)	4.00	.983
My family is interested in the subject I take.	9 (2.5)	16 (4.4)	45 (12.3)	156 (42.6)	140 (38.3)	4.10	.946
I would enjoy a career in STEM field.	8 (2.2)	18 (4.9)	69 (18.9)	142 (38.8)	129 (35.2)	4.00	.968
My family has encouraged me to study subject.	12 (3.3)	14 (3.8)	35 (9.6)	155 (42.3)	150 (41.0)	4.14	.968
I will have a successful professional career and make substantial contribution to the society.	4 (1.1)	14 (3.8)	80 (21.9)	145 (39.6)	123 (33.6)	4.01	.899
I will get a job in my concerned discipline.	6 (1.6)	21 (5.7)	83 (22.7)	135 (36.9)	121 (33.1)	3.94	.966
Some day when I tell others about my career, they will respect me for doing my studies.	1 (0.3)	16 (4.4)	69 (18.9)	164 (44.8)	16 (31.7)	4.03	.840
A career in my subject would enable me to work with others in meaningful ways.	4 (1.1)	16 (4.4)	56 (15.3)	170 (46.4)	120 (32.8)	4.05	.868
Scientists make a meaningful difference in the world.	3 (0.8)	10 (2.7)	44 (12.0)	130 (35.5)	179 (48.9)	4.29	.843
Having a career in STEM fields would be challenging.	8 (2.2)	15 (4.1)	55 (15.0)	162 (44.3)	126 (34.4)	4.05	.925
I would like to work with people who were renowned in my discipline.	6 (1.6)	15 (4.1)	53 (14.5)	155 (42.3)	137 (37.4)	4.10	.907

Opportunities/Challenges about the career	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree	Mean	SD
Building a career in my specialized subject means a lot to me.	13 (3.6)	24 (6.6)	51 (13.9)	138 (37.7)	140 (38.3)	4.01	1.052
It is boring to work as a scientist throughout the life.	40 (10.9)	56 (15.3)	88 (24.0)	103 (28.1)	79 (21.6)	3.34	1.274
Being a researcher in STEM field is an interesting and exciting job.	15 (4.1)	16 (4.4)	72 (19.7)	152 (41.5)	111 (30.3)	3.90	1.018
To become a researcher is a fascinating and an appealing experience to me.	17 (4.6)	24 (6.6)	83 (22.7)	133 (36.3)	109 (29.8)	3.80	1.081
Obtaining recognition from colleagues is important.	7 (1.9)	20 (5.5)	58 (15.8)	156 (42.6)	125 (34.2)	4.02	.945
I can make a theoretical contribution to subject.	8 (2.2)	20 (5.5)	106 (29.0)	138 (37.7)	94 (25.7)	3.79	.960
My aim is to become an authority in my own field.	11 (3.0)	19 (5.2)	81 (22.1)	145 (39.6)	110 (30.1)	3.89	.995
I want to work to find a cure/solution for technological/scientific problem.	4 (1.1)	18 (4.9)	77 (21.0)	153 (41.8)	114 (31.1)	3.97	.905
Present study will help me in achieving my professional goals.	4 (1.1)	17 (4.6)	64 (17.5)	166 (45.4)	115 (31.4)	4.01	.880
I study this programme to become well-off financially.	13 (3.6)	24 (6.6)	53 (14.5)	154 (42.1)	122 (33.3)	3.95	1.030

Source: Computed

To find out the factors leading to opportunities/challenges, 21 attributes that can influence the opinion were identified. The Rotated component matrix for the variables relating to the same is given in Table 12. The KMO test of Sampling Adequacy (.919) indicates that the correlation between pairs of variables explained by other variables and factor analysis is appropriate to this model. Bartlett's Test of Sphericity for push factors with Chi-square = 4779.091 and degrees of freedom 210 with $P < 0.05$ shows a patterned relationship between the items.

Table 12: Opportunities/challenges about the career: Factor analysis

KMO and Bartlett's Test					
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.					.919
Bartlett's Test of Sphericity	Approx. Chi-Square				4779.091
	df				210
	Sig.				.000
Rotated Component Matrix ^a					
Statements	Factors	Component			
		1	2	3	4
I would like to have a career in my area of STEM	Career related	.703	.023	.216	.390
My family is interested in the subject I take		.758	-.080	.209	.225
I would enjoy a career in STEM field		.783	.067	.347	.188
My family has encouraged me to study subject		.763	.076	.206	.124
I will have a successful professional career and make substantial contribution to the society		.723	.451	.073	.100
I will get a job in my concerned discipline		.692	.462	.102	.100
Some day when I tell others about my career,they will respect me for doing my studies		.591	.419	.050	.295
A career in my subject would enable me to work with others in meaningful ways		.542	.484	.175	.330
Scientists make a meaningful difference in the world		.359	.109	.049	.712
Building a career in my specialized subjectmeans a lot to me		.449	.372	.259	.343
It is boring to work as a scientist throughout thelife	Profession related	.004	.472	.295	.067
Present study will help me in achieving my professional goals		.164	.706	.258	.207
I study this programme to become well-off financially		.198	.760	.188	.078
Being a researcher in STEM field is aninteresting and exciting job	Academi crelated	.369	.145	.684	.131
To become a researcher is a fascinating and an appealing experience to me		.284	.220	.798	.108
Obtaining recognition from colleagues is important		.204	.334	.673	.168
I can make a theoretical contribution to subject		.173	.521	.654	.079
My aim is to become an authority in my ownfield		.072	.464	.478	.425
Having a career in STEM fields would be challenging	Personal	.195	.111	.100	.777
I would like to work with people who wererenown in my discipline		.420	.223	.230	.604
I want to work to find a cure/solution for technological/scientific problem		.042	.501	.388	.518
Eigenvalues		9.470	2.037	1.197	1.003
Per cent of total variance explained		45.093	9.698	5.698	4.776
Cumulative per cent of the variance explained		45.093	54.791	60.488	65.264
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.					
a. Rotation converged in 15 iterations.					

Source: Computed

Factor loadings in the rotated component matrix show that the first factor strongly loads opportunities/challenges on ten-factor items. The highest loading is .783, and the minimum loading .359. The second factor loads on three variables, maximum loading is .760 and minimum loading .472. The third factor loads on five variables, maximum loading .798 and minimum loading .478. The fourth factor loads on three variables with maximum loading .777 and minimum loading .518.

Four factors significant to opportunities/challenges, such as Career-related, Profession related, Academic related and Personal, were extracted out of the 21 variables. These factors account for about 65.264 per cent of the variance in the data. The eigenvalue for the first-factor uncertainty is 9.470, which shows that this factor significantly influences opportunities/challenges compared to other factors. The second most crucial factor, called Profession related, accounts for about 9.698 per cent variance with Eigenvalue 2.037. The third-factor discontent accounts for 5.698 per cent of variance with Eigenvalue 1.197. The fourth-factor Personal account for the variance of 4.776 and with Eigenvalue of 1.003.

4.11 Motivational factors

A descriptive statistical analysis was done on the statements related to the students' motivation in higher education. The results of the same are presented in Table 13. the lowest mean value of 3.54 is found to be seen in the statement 'Its relevant to my future career path', and the highest mean value of 7.48 is with the statement 'Having fun'

Table 13: Opportunities/Challenges about the career: Descriptive statistics

Motivational factors	Mean	SD	Percentiles		
			25th	50th (Median)	75th
Gaining degree credit	4.40	2.926	1.00	4.00	7.00
Being paid	6.17	3.364	3.00	7.00	9.00
Having fun	7.48	2.673	6.00	9.00	10.00
Encouraging others to study mysubjects	6.32	2.087	5.00	7.00	8.00
Encouraging others to take a greaterinterest in my subjects	6.05	2.249	5.00	6.00	8.00
Developing transferable skills	4.92	2.437	3.00	5.00	6.00
Looks good on my CV	4.86	2.400	3.00	4.00	7.00
My friends are involved	6.04	2.666	4.00	6.00	8.00
Its relevant to my future career path	3.54	4.517	1.00	2.00	5.00
I enjoy sharing my interest in/enthusiasm for research subjects	4.89	2.985	2.00	4.00	7.00

Source: Computed

The Friedman test shows that it is significant with a p-value less than .05. The least mean rank is 3.4, (Table 14) and for the motivational factor, 'Its relevant to my future career path.'

Table 14: Opportunities/ Challenges about the career: Friedman test

Motivational factors	Mean Rank	Friedman Test	
Gaining degree credit	4.43	Chi-Square	468.243
Being paid	6.18	df	9
Having fun	7.55	Asymp. Sig.	.000
Encouraging others to study my subjects	6.38		
Encouraging others to take a greater interest in my subjects	6.12		
Developing transferable skills	4.99		
Looks good on my CV	4.87		
My friends are involved	6.10		
Its relevant to my future career path	3.40		
I enjoy sharing my interest in/enthusiasm for research subjects	4.97		

Source: Computed

4.12 Suggestions for improvement

A set of variables were given to express the opinion of the students in the various disciplines. A descriptive statistical analysis was conducted and was presented in Table 15. the highest mean value was found to be given for the statement 'Academic, and personal support for students (4.4), and the least mean value is received by the statement 'Collaboration with other higher education institutions' (4.13). Most of the variables have an agreement of more than 80 per cent, which gives strong support given by the respondents.

Table 15: Suggestions for improvement: Descriptive Statistics

Suggestions for improvement	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree	Mean	S D
Collaboration with other higher education institutions	6 (1.6)	8 (2.2)	37 (10.1)	195 (53.3)	120 (32.8)	4.13	.805
Facilities and resources in universities to be enhanced	0 (0.0)	18 (4.9)	19 (5.2)	194 (53.0)	135 (36.9)	4.22	.756
Research collaboration and links with other institutions	1 (0.3)	3 (0.8)	39 (10.7)	193 (52.7)	130 (35.5)	4.22	.686
Better Learning environment is needed	0 (0.0)	6 (1.6)	21 (5.7)	187 (51.1)	152 (41.5)	4.33	.659
Better Research environment is needed	4 (1.1)	11 (3.0)	22 (6.0)	204 (55.7)	125 (34.2)	4.19	.766
Connection between teaching and research from school level	3 (0.8)	5 (1.4)	30 (8.2)	190 (51.9)	138 (37.7)	4.24	.728
Study structure to be revised	5 (1.4)	19 (5.2)	17 (4.6)	189 (51.6)	136 (37.2)	4.18	.847
Curriculum/syllabus must link with innovation	9 (2.5)	5 (1.4)	24 (6.6)	178 (48.6)	150 (41.0)	4.24	.833
Cooperation with other subjects, programmes inside university	4 (1.1)	9 (2.5)	24 (6.6)	200 (54.6)	129 (35.2)	4.20	.758
Management and organisation of university must be improved	3 (0.8)	12 (3.3)	45 (12.3)	178 (48.6)	128 (35.0)	4.14	.813
Internationalization of curriculum and research activities	2 (0.5)	4 (1.1)	40 (10.9)	168 (45.9)	152 (41.5)	4.27	.740
Practical training periods (including placements in industry)	3 (0.8)	5 (1.4)	17 (4.6)	161 (44.0)	180 (49.2)	4.39	.716
Appropriateness of the learning outcomes attained by graduates	4 (1.1)	5 (1.4)	28 (7.7)	181 (49.5)	148 (40.4)	4.27	.751
Employability of Research scholars must be enhanced	4 (1.1)	4 (1.1)	18 (4.9)	162 (44.3)	178 (48.6)	4.38	.730
Academic and personal support for students	2 (0.5)	5 (1.4)	15 (4.1)	166 (45.4)	178 (48.6)	4.40	.686

Source: Computed

To find out the suggestions for improvement, 15 attributes were identified. The Rotated component matrix for the variables relating to scope for improvement is given in Table 16.

The KMO test of Sampling Adequacy (.916) indicates that the correlation between pairs of variables explained by other variables and factor analysis is appropriate to this model. The Bartlett's Test of Sphericity for push factors with Chi-square = 4048.436 and degrees of freedom 105 with $P < 0.05$ shows a patterned relationship between the items.

Factor loadings in the rotated component matrix show that the first factor strongly loads scope for improvement on five-factor items. The highest loading is .813, and the minimum loading 772. The second factor loads on five variables. Maximum loading is .85 and minimum loading 565. The third factor loads on five variables, maximum loading is .761, and minimum loading is .519.

Three factors significant to push motivation, such as Academic support, learning support and Interconnections, were extracted out of the 18 variables. These factors account for about 72.419 per cent of the variance in the data. The eigenvalue for the first-factor Academic support is 8.127, which shows that this factor significantly influences the scope of improvement compared to other factors. The second most crucial factor, called Learning support, account for about 11.362 per cent variance with Eigenvalue 1.704. The third-factor Interconnections account for 6.877 per cent of variance with Eigenvalue 1.032.

Table 16: Suggestions for improvement: Factor Analysis

KMO and Bartlett's Test				
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.				.916
Bartlett's Test of Sphericity	Approx. Chi-Square			4048.436
	df			105
	Sig.			.000
Rotated Component Matrix ^a				
Statements	Factors	Component		
		1	2	3
Internationalization of curriculum and research activities	Academic support	.772	.257	.222
Practical training periods (including placements in industry)		.813	.118	.268
Appropriateness of the learning outcomes attained by graduates		.782	.226	.262
Employability of Research scholars must be enhanced		.778	.223	.327
Academic and personal support for students		.789	.216	.236
Collaboration with other higher education institutions	Learning support	.143	.850	.149
Facilities and resources in universities to be enhanced		.146	.807	.336
Research collaboration and links with other institutions		.225	.850	.209
Better Learning environment is needed		.304	.751	.162
Better Research environment is needed		.363	.565	.510
Connection between teaching and research from school level	Inter	.416	.423	.519

Study structure to be revised	Connections Inter connections	.193	.477	.687
Curriculum/syllabus must link with innovation		.327	.148	.761
Cooperation with other subjects, programmes inside university		.240	.208	.746
Management and organization of university must be improved		.350	.195	.735
Eigenvalues		8.127	1.704	1.032
Per cent of total variance explained		54.181	11.362	6.877
Cumulative per cent of the variance explained		54.181	65.542	72.419
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.				
a. Rotation converged in 15 iterations.				

Source: Computed

4.13 Curricula and General Study Process

A set of variables were given to the respondent to express their opinions on the improvement needed in the curricula and general study process in higher education institutions. The highest mean value is expressed for Thinking skills (4.65), and the lowest mean value is received for the statement 'Intercultural skills' (4.32). Table 17 gives a picture that more than 80 per cent of the respondents support the various skills meted out by the statements.

Table 17: Curricula and general study process: Descriptive statistics

Curricula and General Study Process	Not important	Rather not important	Neutral	Rather important	Very important	Mean	S D
Communication skills (ability to listen, express and present ideas, ability to persuade, to negotiate etc.)	0 (0.0)	1 (0.3)	19 (5.2)	96 (26.2)	250 (68.3)	4.63	.596
Personal skills (self-confidence, positive attitude, strong work ethic etc.)	0 (0.0)	3 (0.8)	14 (3.8)	98 (26.8)	251 (68.6)	4.63	.600
Interpersonal skills (ability to work in a team, ability to manage conflicts, networking etc.)	6 (1.6)	5 (1.4)	23 (6.3)	88 (24.0)	244 (66.7)	4.53	.810
Intercultural skills (command of more than one language, work in culturally diverse teams etc.)	3 (0.8)	8 (2.2)	42 (11.5)	128 (35.0)	185 (50.5)	4.32	.824
Learning skills (ability to learn independently; curiosity and drive for continuous learning etc.)	0 (0.0)	11 (3.0)	21 (5.7)	101 (27.6)	233 (63.7)	4.52	.739

Curricula and General Study Process	Not important	Rather not important	Neutral	Rather important	Very important	Mean	S D
Entrepreneurial skills (flexibility, opportunity seeking, risk-taking etc.)	0 (0.0)	6 (1.6)	43 (11.7)	119 (32.5)	198 (54.1)	4.39	.757
Thinking skills (critical, analytical, strategic thinking etc.)	0 (0.0)	7 (1.9)	12 (3.3)	82 (22.4)	265 (72.4)	4.65	.639
Information, media and technology skills (ability to obtain and process information)	0 (0.0)	3 (0.8)	30 (8.2)	102 (27.9)	231 (63.1)	4.53	.681
Virtual collaboration skills (ability to work productively in a virtual team/environment)	2 (0.5)	10 (2.7)	26 (7.1)	117 (32.0)	211 (57.7)	4.43	.787
Technical skills (professional field related skills to accomplish specific tasks etc.)	0 (0.0)	5 (1.4)	21 (5.7)	98 (26.8)	235 (64.2)	4.57	.669

Source: Computed

For identifying the significant determinants of curricula and the general study process, factor analysis was applied to the response provided by the respondents, as shown in Table 18. Ten determining factors were identified. The respondents were asked to express their level of opinion on the influence of each of these factors on a five-point Likert scale.

Table 18: Curricula and general study process: Factor analysis

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.926
Bartlett's Test of Sphericity	Approx. Chi-Square	1672.022
	df	36
	Sig.	.000
Rotated Component Matrix ^a		
Statements	Component	
	1	
Communication skills (ability to listen, express and present ideas, ability to persuade, to negotiate etc.)	.686	
Personal skills (self-confidence, positive attitude, strong work ethics etc.)	.737	
Interpersonal skills (ability to work in a team, ability to manage conflicts, networking etc.)	.762	
Learning skills (ability to learn independently; curiosity and drive for continuous learning etc.)	.771	
Entrepreneurial skills (flexibility, opportunity seeking, risk-taking etc.)	.798	
Thinking skills (critical, analytical, strategic thinking etc.)	.802	

Statements	Component
	1
Information, media and technology skills (ability to obtain and process information)	.795
Virtual collaboration skills (ability to work productively in a virtual team/environment)	.728
Technical skills (professional field related skills to accomplish specific tasks etc.)	.686
Eigenvalues	5.210
Per cent of total variance explained	57.886
Cumulative per cent of the variance explained	57.886
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.	
a. Rotation converged in 15 iterations.	

Source: Computed

Higher values of Kaiser-Meyer-Olkin (KMO) test of sampling Adequacy (.926) indicates that the correlation between the pairs of variables as explained by other variables and thus the factor analysis is considered appropriate for the model. The Bartlett's test of Sphericity for enterprise growth, approximate Chi-Square 1672.022 with degrees of freedom ten and $P < 0.05$, show a patterned relationship between the items and the correlation matrix measures are significantly making the factor analysis appropriate.

Factor loadings in the Rotated Component Matrix show that the factors load on all ten items. The highest loading .802 for the factor "Thinking skills" and minimum loading .686 for "Communication skills". The extracted component from factor analysis, namely, the Curricula and general study process, account for about 57.886 per cent variance in the data. The Eigenvalue for the factor is 5.210, which indicates that this factor provides the highest information on the growth of the enterprise. This factor offers maximum insight into elements influencing the curricula and general study process.

4.14 Aspects Related to STEM Jobs

Various aspects needed for securing a STEM job are analyzed in this section. A descriptive statistical analysis was done and presented in Table 19. The highest mean value (4.51) is received by the statement "Provide post-graduation support," and the lowest mean value (3.28) is received by the statement "Study experience abroad." Around 80 per cent of the respondents support the statements.

Table 19: STEM Jobs and the various aspects: Descriptive statistics

Aspects of Job	Not important	Rather not important	Neutral	Rather important	Very important	Mean	SD
Prepare courses more relevant to the labour Market	4 (1.1)	9 (2.5)	47 (12.8)	128 (35.0)	178 (48.6)	4.28	.859
Include practical tasks and assignments in the courses	0 (0.0)	4 (1.1)	27 (7.4)	116 (31.7)	219 (59.8)	4.50	.681
Include sector specific work placements as an integral part of the study Programme	3 (0.8)	3 (0.8)	32 (8.7)	129 (35.2)	199 (54.4)	4.42	.753
Provide post-graduation support (facilitate relations between graduates and companies)	1 (0.3)	6 (1.6)	28 (7.7)	103 (28.1)	228 (62.3)	4.51	.732
Provide ongoing collaboration with the labour market actors	2 (0.5)	8 (2.2)	36 (9.8)	121 (33.1)	199 (54.4)	4.39	.795
Field related	3 (0.8)	17 (4.6)	55 (15.0)	119 (32.5)	172 (47.0)	4.20	.917
Academic qualifications	2 (0.5)	10 (2.7)	30 (8.2)	108 (29.5)	216 (59.0)	4.44	.801
Study experience abroad	39 (10.7)	72 (19.7)	82 (22.4)	95 (26.0)	78 (21.3)	3.28	1.290
Field related internship experience (locally)	4 (1.1)	26 (7.1)	85 (23.2)	148 (40.4)	103 (28.1)	3.87	.940
Field related internship experience (abroad)	33 (9.0)	66 (18.0)	79 (21.6)	107 (29.2)	81 (22.1)	3.37	1.258
Specific professional skills and knowledge	2 (0.5)	12 (3.3)	44 (12.0)	146 (39.9)	162 (44.3)	4.24	.829

Source: Computed

For identifying the main elements of STEM Jobs and the various aspects, factor analysis was applied to the response provided by the respondents, as shown in Table 20. Eleven determining factors were identified. The respondents were asked to express their level of opinion on the influence of each of these factors on a five-point Likert scale.

The value of Kaiser-Meyer-Olkin (KMO) Test of Sampling Adequacy (.838) indicates that other variables explain the correlation between the pairs of variables. Thus, the factor analysis is considered appropriate for this model. The Bartlett's Test of Sphericity for economic factors, approximate Chi-square 1778.659 with degrees of freedom 55 and P less than 0.05 shows a patterned

relationship between the items, and the correlation matrix measures significantly making the factor analysis appropriate.

Factor loadings with the rotated component matrix show that the first factor strongly loads on six items. The highest loading is .847 for the factor "Include sector-specific work placements as an integral part of the study Programme" and the minimum loading .447 for "Academic qualifications". The second-factor loads on five items. Maximum loading for "Field-related internship experience (abroad)" is .858 and minimum loading for "Specific professional skills and knowledge" is .266.

Table 20: STEM Jobs and the various aspects: Factor Analysis

KMO and Bartlett's Test			
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.			.838
Bartlett's Test of Sphericity	Approx. Chi-Square		1778.659
	df		55
	Sig.		.000
Rotated Component Matrix ^a			
Statements	Factors	Component	
		1	2
Prepare courses more relevant to the labourMarket	Labour market Connectivity	.776	.200
Include practical tasks and assignments in thecourses		.803	.049
Include sector specific work placements as anintegral part of the study Programme		.847	.163
Provide post-graduation support (facilitate relations between graduates and companies)		.822	.025
Provide ongoing collaboration with the labourmarket actors		.834	.108
Academic qualifications		.447	.288
Field related work experience	Field experienceand skills	.357	.641
Study experience abroad		.023	.836
Field related internship experience (locally)		.089	.805
Field related internship experience (abroad)		.027	.858
Specific professional skills and knowledge		.212	.266
Eigenvalues		4.313	2.134
Per cent of total variance explained		39.205	19.399
Cumulative per cent of the variance explained		39.205	58.604
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.			
a. Rotation converged in 15 iterations.			

Source: Computed

The Factor Analysis extracted two components significant to STEM Jobs and the various aspects, namely, Labour market Connectivity and Field experience and skills. These components account for about 58.604 per cent of the variance in the data. Labour market Connectivity comprises of six items. The Eigenvalue

for the same is 4.313, which indicates that this factor contains very high information than the other factors. Field experience and skills elements comprise five items. The Eigenvalue for the item is 2.134 accounting for about 19.399 per cent of the variance.

5. Conclusion

DeCoito (2014) pointed out that students' lack of interest in math and science necessitates better classroom teaching techniques and chances to illustrate real-world applications and potential jobs. A vital goal of the STEM pipeline is to help students recognize the links between STEM education and future employment prospects. Salzman (2013) argues that data does not appear to support allegations of labor shortages in STEM fields or an apparent inability of the market to create enough workers. Assessing the supply and demand for STEM professionals necessitates a more comprehensive examination of the context and evidence. The government has been accused of failing to address the lack of STEM employees by neglecting to take action. According to some, STEM is a "leaking pipeline," with students abandoning college because it is too harsh or unprepared. However, proponents of supply crisis allegations go even further, claiming that STEM disciplines are in short supply "pipeline that is leaking "

A detailed analysis of the students who are currently doing their graduation in STEM fields was conducted. It is found that the higher education institutions work under government, aided and self-financing institutions do play a great role in catering to the needs of the graduates in STEM fields. The various social, demographic, and geographic variables influence students' decision to pursue higher education in STEM fields. The study provisions and study conditions existing in the higher education institutions for STEM graduates include course specific, teaching and evaluation as well as extra-curricular activities. the issues with the curricula and General study process that exist in the higher education institutions for STEM graduates include career-related, profession related, academic related and personal.

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The politics of health innovations: Unpacking the role of industry associations in the development and diffusion of health innovations

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Abstract

This paper focuses on the politics of health innovation, seeking to unpack the role of industry associations in facilitating the growth and development of healthcare technologies industries in India. Conceptualising industry associations as intermediary institutions within innovation systems, the paper explores their emergence and vital role in the evolution of the Indian medical device industry. The latter is a crucial innovation in the healthcare sector. We argue that the absence of sector-specific associational representation of the interests of the domestic medical device industry created both communication and knowledge gaps between this industry and the government. As a consequence of these gaps, for a number of years, the Indian government appeared to neglect the medical devices industry in the country, inhibiting innovation and restricting the growth of domestic firms. All this changed in 2005 with the emergence of multiple industry-specific associations, which started playing a critical role in shaping the government's industrial and regulatory policies, promoting entrepreneurship and bridging knowledge gaps between the government and the health industry. The ability of industry associations to reduce transaction costs makes them an indispensable part of innovation systems and impactful actors in health politics. However, the different political and policy agendas dominating their positions raise questions about their development impact.

Keywords: Politics of health, innovation systems, industry associations, health and industrial policy, India, the medical device industry

1. Introduction

Health is defined by the World Health Organisation (WHO) as ‘... a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity’. This definition is focused on individuals and, at first glance, has nothing to do with politics, i.e., the process concerned with the reproduction of society through government and state institutions. Yet health systems and related technological innovations are very much influenced by political decisions about policy, structures, funding, and procurement of health products and services. To make matters even more complex than this, in between health innovation systems and governments, there seems to exist what Sabatier (1991) describes as the ‘policy subsystem’ comprised of ‘those actors from a variety of public and private organisations who regularly seek to influence policy’ (Jenkins-Smith & Sabatier, 1994, p. 179). Among them are industry associations that use their collective voice to direct the state toward making specific decisions that serve their members' interests (Cavazos and Szyliowicz, 2011). Papaioannou et al. (2016) argue that industry associations play an important role, as intermediaries, in building institutional capacities for innovation, shaping innovation policy and influencing subsequent technological trajectories. Such actors are thought to be particularly important in developing countries, where national innovation systems lack capacities for facilitating innovation and where effective linkages between government and industry, a key mechanism for building capacities, are bound to be lacking (Kshetri & Dholakia, 2009).

Industry associations viewed here ‘as member-based organisations that represent the interests of a particular industry and actively lobby and negotiate with government on their members’ behalf to shape government policy and regulation’ (Watkins et al., 2015, p1408) are credited with facilitating the innovation process by performing various activities, including advising, negotiation, mediation and knowledge transfer (Nadvi, 1999; McMillan and Woodruff, 1999). In this way, industry associations are viewed as compensating for institutional inadequacies in the business environment by informing the government about their members' needs and acting as a nodal point for coordination activities with different stakeholders of health innovation systems (Newel, 2003; Faulkner, 2009).

Industry associations, however, are also criticised for their rent-seeking behaviour and for pursuing the narrow interests of their members (Cavazos and Szyliowicz, 2011; Scoones, 2003). In this way, it is argued that such groups can distort industrial policy to such an extent that it becomes detrimental to other stakeholders and inhibits innovation (Athreye & Chaturvedi, 2007). In addition, when threatened with radical technological change, associations tend to shape industry conditions and policies to suppress the diffusion and adoption of innovation (Cavazos and Szyliowicz, 2011). Recently, Mazzucato

(2013; 2018; 2021) has confirmed that associations often concentrate their lobbying efforts on earning unproductive rents and convincing governments to deregulate health industries and reducing taxation without paying enough attention to investment for innovation.

Despite these misgivings, the existing innovation literature positions industry associations as actors that are critical to the development and growth of innovative industries, including pharmaceuticals. Successful associations are those which effectively bridge differences between members, forge substantive links to government and move beyond narrow rent-seeking to work toward broader industry 'development' goals (Papaioannou et al., 2016). An association's ability to do so is based on the confluence of organisational capacities and exogenous factors, including industry, market and political contexts (Reveley & Ville, 2010).

If it is indeed true that industry associations are critical to health industry growth and their intermediary role in institutional capacity building is particularly significant for developing countries, it becomes important to ask: in what way and under what circumstances do industry associations emerge within innovation systems and become effective in drawing the attention of the government to a specific health industry?

The paper addresses this question by looking at the historical emergence and role of industry associations in the evolution of the Indian medical device sector. This sector was initially underrepresented by established industry associations and lacked sector-specific representation. Therefore, it has struggled with industry expansion and technological capability development in India. The country has a well-established knowledge-driven health industry. Also, its pluralist policy context allows for a diverse set of stakeholders, including a few health-specific industry associations, to compete for influence (Athreye & Chaturvedi, 2007; Abuduxike & Aljunid, 2012). The Indian medical device sector had negligible representation up to 2005. Since then, it has received effective representation from multiple sector-specific and umbrella industry associations, which had a significant impact on the industrial growth of medical devices.

The data for this paper was collected in two phases. In the first phase, a pilot study was carried out on innovative activities in healthcare delivery, revealing systemic interactions between associations, government and other stakeholders in the medical device sector. In the second phase, the primary data was collected through conducting interviews with stakeholders and associations representing the medical device sector in India. In total.

This paper draws on the literature of industry associations as institutional intermediaries within innovation systems to show how the overlooked medical

devices sector in India, through effective associational representation, succeeded in drawing the attention of the government and shaping institutional capacities at the macro level as well as technological trajectories at the micro level.

The remainder of this paper is structured as follows. Section 2 reviews the literature on industry associations as intermediaries within innovation systems, along with the potential and challenges that such institutional actors offer in the context of developing countries. Section 3 presents the research methodology, while section 4 discusses the impact of changing economic and political context on industry associations in India. Section 5 focuses on the case of medical device industries and the effect of associational representation. Section 6 provides further analysis and discussion. Section 7 concludes the paper by summarising the main argument.

2. Industry associations as intermediaries within innovation systems

Innovation systems can be generally defined as ‘... all important economic, social, political, organisational, institutional, and other factors that influence the development, diffusion and use of innovation’ (Edquist, 2005: 182). Innovation Systems (IS) theory at different levels (sectoral, regional, national, and global) highlights interactions between institutions as an essential precondition for new knowledge generation and industrial capacity building (Lundvall, 1992; Arrow 1962). These interactions, particularly between government and industry, facilitate knowledge exchange and collective learning towards industrial development and public advancement. IS theorists view learning and subsequent innovation as a nonlinear and recursive process that relies on effective feedback loops between actors and institutions, and place considerable emphasis on both the evolutionary and path-dependent nature of innovation. In this way, historical contexts and changing institutional dynamics matter. From a path-dependent perspective, relations and dynamics between actors and institutions influence technological and development trajectories that, once set, are considerably difficult to change even when better alternative trajectories are apparent. At the macro-level, relations between government and industry can take on several forms, all of them involving some degree of corporatism i.e., cooperation between government and industry. Yet, as innovation scholars have shown, this corporatism sometimes enables the generation of new products and processes, and some other times inhibits it. For example, scholars such as Dalziel (2006) provide early evidence for industry associations as enablers of innovation through knowledge exchange and training. Others such as Cavazos and Szyllowicz (2011) claim that industry associations, in fact, suppress innovation when the latter threatens the profit and survival of their members.

Industry associations as intermediary actors

In the innovation systems literature, there is a growing awareness of intermediaries which function in the midst of users and producers of knowledge. In fact, intermediaries facilitate knowledge exchange and collaboration between actors, particularly firms, and increasingly between institutions, including between government, market and industry. These include a variety of technology transfer organisations, consulting and strategic business services firms and hybrid funding organisations, including venture capital firms, and, more recently, industry and trade associations (Davenport et al., 1999). As intermediaries, these actors are viewed as network builders, functioning as mechanisms for information collection and exchange, engaged in selecting network members and subsequent technologies and determining network structure and norms, as well as managing collaborative relations between network members (Clayton et al, 2018). According to Klekx & Leeuwis (2009), intermediaries act as ‘innovation brokers’ by assisting in connecting the different components of global, international, national, sectoral and /or regional innovation systems. Where studies have looked at how interactions between micro-level firm processes and macro-level institutions encourage the emergence of new innovations and technological trajectories, such intermediaries are found to play a critical role. For example, work by Bergek et al., (2008) and Hekkert & Negro (2009) looks at the successful development and commercialisation of various clean technology innovations in Germany, suggesting that it is government, at the national level, that initially stimulates entrepreneurial activity, through which initial yet limited markets emerge. Industry associations engage in collective bargaining, self-regulation (through the development and protection of standards) and lobbying the government on behalf of their members for greater incentives; this decreases uncertainty which encourages further investment and subsequent market growth. This process, punctuated by virtuous cycles and vicious cycles (e.g., initial regulation proves ineffective) (Hekkert & Negro, 2009), demonstrates that politics and negotiations, facilitated by intermediary actors such as industry associations, are both inevitable and central as processes through which institutions and subsequent policy are informed. Yet, as more recent work by Yao et al (2022) demonstrates, there is a dark side to institutional intermediaries too. They can reduce both autonomy and flexibility of firms, constraining their ability to experiment and innovate.

Industry associations, innovation and developing countries

Innovation studies which position industry associations as intermediaries that facilitate innovation are few, with Watkins et al., (2015) suggesting that early innovation systems literature does not sufficiently consider ‘politics’ and related intermediary organisations that work with the state to inform and steer conditions and incentives for innovation and growth within particular

industries and technological sectors. That said, studies that purposely connect the activities of industry associations to innovation have appeared more regularly in the organisational management and development literature. For example, the work of Dalziel (2006), Kautto (2007), Reveley & Ville (2010), Kahl (2014), Spillman (2016) and Yao et al (2022) demonstrates that industry associations facilitate collaboration between members, build coalitions and diffuse new technology by actively engaging in technology adoption and training, standard setting and influencing regulation, legitimacy increase and social acceptance. In the international development literature, several empirical studies have highlighted the beneficial effects of industry associations and broader business groups on industrial development in developing economies (Lucas, 1993; Nadvi and Schmitz, 1994; McMillan and Woodruff 1999; Watkins et al, 2015; Papaioannou et al, 2016). According to Marques (2017: 745) 'The developmental state in many developing countries relied heavily upon business associations as a mode of economic organisation – the Japanese government, for example, ... promoted and helped organise sector-specific associations as a means of enhancing productivity and monitoring compliance with agreed upon objectives right up to the 1980s'. This is still very much the case in emerging economies such as China where government directly intervenes in the economy. According to Yao et al (2022: 2) 'Governments, especially those of emerging markets, increasingly support and intervene in institutional intermediaries, often through the use of taxation policies, in the hope that this will increase the innovativeness of private firms and lead to growth'. In the area of health innovation, Papaioannou et al., (2016) point to the importance of industry associations in the transfer of global knowledge on standards and practices to the national and local level, highlighting the competing interests between global institutions and multi-national companies (MNCs) and those of governments, civil society and local industry players. Athreye & Chaturvedi (2007) suggest that one common factor emphasised in all these studies is the new nature of competition faced by members of these associations and their desire to overcome common problems through collective action and support from the state.

Industry associations: the politics of innovation and development?

Papaioannou et al. (2016) suggest that early NIS theory ignores the emergence of industry associations and their importance for innovation and development. The absence of industry associations from these discussions is due, in part, to the omission of politics from early NIS theory. This theory tended to overlook the relationship between innovation systems - the set of institutions which facilitate the generation and diffusion of new technologies (Watkins et al, 2015; Metcalfe, 1997) - and political systems - the set of institutions which interact to facilitate political decisions about the allocation of resources and achievement of social goals (Easton, 1957; Almond & Coleman, 1960). The two sets of

institutions together constitute a framework within which government and industry, and other actors negotiate policies to influence the innovation and development process. Recognition of this framework came from liberal economists working in the public choice and transaction cost traditions in the 1950s and 1960s. Public choice can be regarded as branch of rational choice theory that uses liberal economic methods to study politics. Within public choice, the theory of collective action and the rent-seeking theory of public policy making were crucial for conceptualising industry associations as interest groups (Marques, 2017). In his *Logic of Collective Action*, Olson (1965) argued that only groups with narrow special interests such as industry associations might be effective in influencing government action. This argument was taken forward by Buchanan et al (1980) who modelled policymaking as a political market operating under the rules of supply and demand of policies. In this context, industry associations might be seen as rational actors, putting forward demands and incentives for pro-innovation policies which benefit their members. Although the public choice theorisation of industry associations ignored the complexity of policy-making and the contradictory nature of the state, it led to the re-birth of political pluralism or neo-pluralism as a theory that conceives the democratic process in terms of the interaction of competing interest groups (Dahl, 1983), with power diffused on pluralist lines among strong associations (Smith, 2006).

Focusing on the issues of power and politics, Bachrach & Baratz (1962) show that power in terms of agenda setting is multifaceted. They discuss the 'two faces' of power: the first is centred in the authority to choose and make decisions; the second is concerned with the ability to influence what issues are considered in the first place. Bachrach & Baratz (ibid) argue that the second face is potentially more important than the first, and, in this context, the capability of industry associations in capitalist economies to influence decision makers is well established. Some researchers have criticised the direct (shaping what gets onto the agenda) or indirect (influencing others who do shape the agenda) influence of industry associations on the policy-making process. For example, Athreye & Chaturvedi (2007) point out that often these small groups can capture power and extract rents at the expense of society at large; giving rise to justifiable fears that lobbying actually distorts industrial policy.

3. Research methodology

This research employed a case study approach focusing on the Indian medical devices sector. India was selected because of its active involvement in health innovation, a well-established knowledge-driven health industry and its pluralist policy context that allows a diverse set of stakeholders, including a number of health-specific industry associations, to compete for influence (Athreye & Chaturvedi, 2007; Abuduxike & Aljunid, 2012).

The data collection for this research was carried out in two phases. In the first phase, a pilot study was carried out on innovative activities in healthcare delivery, revealing systemic interactions between associations, government and other stakeholders in the biotechnology and medical device sector. The primary data for the second phase was collected through conducting interviews with stakeholders and associations representing these two sectors in India. In total, 30 interviews were conducted involving senior managers and policymakers from three types of innovation actors: industry specific associations i.e. the Organisation of Pharmaceutical Producers of India (OPPI), the Association of Biotechnology Led Enterprises (ABLE) and the Indian Pharmaceutical Association (IPA); umbrella organisations i.e. the Confederation of Indian Industry (CII) and the Federation of Indian Chambers of Commerce and Industry (FICCI); and finally related stakeholders i.e. the Indian Biotechnology Industry Research Assistance Council (BIRAC), PriceWaterhouseCoopers (PWC), Serum Institute, Glaxo Smith Cline (GSK), Achira Labs, AiMED (Association of Indian Medical Device Industry) and Sree Chitra Research Institutes. We interviewed multiple representatives from each of these different stakeholders and concluded primary data collection when additional interviews failed to produce substantial new insights. The interviews, which were audio- recorded and later transcribed, lasted 30 to 90 minutes with a mean duration of 40 minutes. Lists of documents and interviewees were identified through an initial pilot study of health industry associations that took place in India. Interview questions focused on their context and historical background, their main activities and their function as public actors of development. Empirical data were triangulated with other sources, including government publications, research journal articles, consultancy reports and media releases. We enriched our findings by integrating these interviews into the cases.

We drafted a case history on the role of industry associations in the evolution of medical device sectors based on secondary data. We first compiled facts and quotes from key players from archival sources such as news articles, industry newsletters, and association annual reports. Next, we refined our data analysis by conducting a content analysis of interviewees' transcripts using pattern matching technique (Miles and Huberman, 1984). We analysed data relating to three types of activity: regular systemic policy interactions of industry associations with public and private actors; specific broker activities of industry associations targeted at creating financial incentives for its members; and the development of platforms of knowledge diffusion and industry promotion, including conferences, and workshops. This allowed us to codify constructs of interest and establish the appropriate meanings and relationships between concepts. This helped us to examine how firms organised themselves to influence policy processes and to account for the different degrees of influence they have been able to exercise. Examination of the historical context of

policymaking helps identify patterns of change that earlier policies have induced or sustained. It aids in capturing the contribution of distinct interest groups that represent various levels of historical and existing power, all working through an incremental and adaptive process.

4. The changing economic and political context in India: from anti-business to pro- business

India's transformation from a controlled anti-business economy to a liberalised pro-business economy provides a significant twist to the role of industry associations. This change in the economic and political environment transformed the power dynamic among different stakeholders shifting policy context towards less coherence. The pre-independence era witnessed the emergence of the multiple industry organisations (Kotchanek, 1995-1996). The three most prominent associations representing the private sector in India, i.e., the Federation of Indian Chambers of Commerce and Industry (FICCI), the Associated Chambers of Commerce and Industry (ASSOCHAM) and the Confederation of Indian Industry (CII), have their origins in the pre-independence period. These organisations are still very active in influencing the policy environment but differ considerably in age, size, number of interests represented and resources (see Table 1).

Table 1 Key characteristics of Indian umbrella/apex industry organisation

No	Name	Year	Nature of members
1	Assocham	1920	the oldest and now represents both large family-owned indigenous business and foreign multinationals
2	FICCI	1927	the largest, most broadly based apex association and tends to represent older, more traditional, indigenous, family-owned business
3	CII	1982 (merger of the Indian Engineering Association which had been created by British entrepreneurs in 1895 and the Engineering Association of India founded by Indian capital in 1942)	the newest and richest apex association and tends to represent newer sunrise industries including electronics, software and computer technology.

Post-independence in 1947, the Indian government adopted protectionist policies guided by the ideas of import substitution and inspired by Marxist – socialist beliefs of redistribution and equity. In this period, the Indian policy environment was dominated by strong government intervention with significant beliefs in the capability of the public sector and limited trust in domestic firms and their industry associations. During this period, industry associations in India mainly acted as supplicants in their dealings with the government and were reactive rather than proactive about setting policy agendas (Kochaneak, 1995-1996).

In the 1980s, the economic climate began to change in favour of a more pro-business agenda, and that gave rise to a change in the role of industry associations. Kochanek (1995-1996) suggests that during the 1980s, FICCI and ASSOCHAM reorganised and increasingly became mirror images of each other (with differing regional bases), strongly supporting protective policies. In contrast, the CII represented more narrow pro-business interests, including emerging technology, export-oriented businesses, and more ‘modern’ industries that favoured a more open, competitive economy and a stronger integration with the global economy (Kohli, 2006). The different positions taken by these organisations signalled a clear split in their political and policy preferences. Sinha (2005) suggests that the government needed support from industry for liberalisation of the economy and found an ally in the CII. Both government and the pro-business industry associations, especially the CII, took steps to work in tandem to achieve mutually beneficial objectives. This was the beginning of ‘pro- business policies’ (Kohli 2006) – an informal social contract between the firm and the state. Ghose (2010) refers to this transformation as ‘a shift in how the state and the firm could collude and share a common goal, forged on meshing framings of risk based on an explicitly crafted space for the firm and the state to collude, though mostly behind closed doors’.

Kohli (2006) points out that the major policy changes were ‘pushed forward by a narrow coalition, in processes characterised by ‘stealth’ rather than by open democracy. In fact, as Cali and Sen (2011) argue, along with the CII, the export-oriented sectors of the Indian industry, MNCs and the Indian government entered into a ‘growth coalition’, aimed at enhancing economic growth through increasing the rate of investment in technological innovation and the productivity of investment. Together, the advent of economic liberalisation and the integration of lobbying into the political process of policy making opened a space that had hitherto not existed, leading to the transformation in some parts of that process (Athreye & Chaturvedi, 2007). The informal social contract between the firm and the state expanded exponentially after the economic liberalisation policies adopted by the Indian government in 1991.

The balance of payment crisis in 1990 and pro-liberalisation political leadership ushered in economic liberalisation and changed the trajectory of India's trade policy. This period was marked by the increasing role of industry associations in shaping the economic and trade policy in the interests of their members. The integration of the Indian economy with the global economy emerged as a contentious issue among different industry associations. Kohli (2006) contends that over the next decade, the active role of industry associations in setting policy agendas became ever more institutionalised, with senior government policy officials inviting the private sector to be part of the decision-making.

Economic liberalisation and openings for foreign capital brought more scrutiny from domestic and international stakeholders. In this emerging economic and political environment, the political process surrounding policy making started getting more complex, with different stakeholders with unequal access to power exerting significant pressure on the policy makers. This became prominently evident in the healthcare sector. This new model of the healthcare industry dominated by international financial and development institutions promoted FDI for innovation, with technology and knowledge emerging as buzzwords despite poor access and affordability for the majority, poor indigenous capability to produce high-end technologies, and insufficient regulatory mechanisms. The complicated political process of repealing the 1970 Act and transitioning to the full implementation of the TRIPS requirements is illustrative of government-industry relations during times of extreme regulatory uncertainty. Lobbying by industry associations has been credited for the acceptance of TRIPS as part of the WTO agreement by the Indian government (Ramanna, 1999). This had a tremendous impact on innovation in the health sector. The two leading industry associations, IPA and OPPI, heavily advocated India's adoption of the TRIPS requirements. In tune with this, umbrella organisations such as CII, FICCI and ASSOCHAM began to advocate the need for greater patent protection and started supporting the bill to amend patent laws in conformity with the TRIPS agreement. Yet, with the emergence of vocal civil society organisations and judiciary activism, all these began to change. Specifically, in healthcare, civil society and judicial activism began to encroach on areas of governance and policymaking. In turn, industry associations began to react to this, further complicating the policy-making process.

Overall, the introduction of economic liberalisation, and the emergence of influential civil society organisations and judicial activism – in parallel with the involvement of international institutions – have given rise to a new form of government-industry interaction. This transformation in the Indian business environment provides an interesting background to understand the role and significance of industry associations in the development of medical device industries.

5. The medical devices industries

The Indian healthcare sector is estimated to be valued at US \$ 372 bn in 2022, with medical devices and diagnostics, pharmaceutical and biotechnology industries representing the three critical healthcare innovative industries. The Indian state established government committees (such as the Hathi committee, Mashelkar Committee) for industrial sub-sectors to set up guidelines for prioritisation, production, regulation, pricing and restricting imports to promote indigenous production and link up with social conditions, especially the needs of healthcare infrastructure.

The medical device industry generates products – instruments, apparatus, and appliances – for ‘diagnosis, prevention, monitoring, treatment or alleviation of disease or compensation for an injury or handicap . . . which does not achieve its principal intended action in or on the human body by pharmacological, immunological or metabolic means’ (MHRA, 2013). The Indian medical device industry was estimated to be worth US \$ 4.5 bn in 2012 and growing at 14 per cent per annum (WHO, 2012). Currently, it is the fourth largest in Asia worth US \$ 15 bn. However, this industry is not well documented, and estimates of its size vary significantly across different sources. There are about 14,000 medical devices marketed in India, divided into key segments of instruments and appliances used in ophthalmic, dental, and orthopaedic treatments, and for diagnostic purposes. Over the years, the country has become increasingly dependent on imports from countries like the US, Japan, the UK, France, Finland and Germany. Commenting on the state of the Indian medical device industry, Kamath (2010) points out that the words India and medical technology tend not to be used together.

In 2012, Indian imports stood at 1.14 per cent of the global import of medical devices, while the export share constituted less than 0.5 per cent of total global exports (Datta et al., 2013). The Indian total trade (imports plus exports) in medical devices has steadily risen from 2005 to reach US\$ 2.1 bn in 2010 (WHO, 2012). According to Datta et al., (2013), in 2010, there were around 356 medical device-manufacturing units accounting for only 0.19 per cent share of the total Indian manufacturing industry. However, increasing imports show that in most segments, Indian firms are still struggling either to develop devices suitable for local use or find acceptance for their products in global markets. This remains the case in 2022, given that India imported medical devices worth Rs 63,200 crore in 2021-2022, up 41% from Rs 44,708 crore in 2020-2021.

Coevolution of the Indian medical devices industry and industry associations

The Indian medical device industry is highly fragmented, with approximately 360 domestic medical device manufacturers covering different segments (Table 2).

Table 2 Medical devices industry segments (Deloitte 2016)

Indian Medical Devices Industry	Consumables and implants including stents, syringes, needles, catheters, suturing materials, bandages and dressing	Instruments and appliances including surgical and non-surgical equipment, and other instruments and supplies
	Diagnostic Imaging including electro-diagnostic apparatus, radiation apparatus, imaging parts and accessories	Patient aids and others including hearing aids, prosthetics and orthotics, pacemakers and other

Indian firms are strong players in the low-tech medical device market for furniture and other products which do not come in direct use in treatment. However, only a few Indian firms are engaging in the production and development of critical care and surgical devices (Datta et al., 2013). The status of the medical industry is captured by the following introductory paragraph in a vision document CII published in 2015,

Little is known about the medical technology industry in India today. Even estimates of market size vary significantly. Pricing is not transparent to the consumer leading to a general perception that it is dominated by large imports from foreign multinationals that are self-seeking and profit-making. Little has been done to address this perception

This indicates that, unlike other healthcare technology sectors, the medical device sector suffered from a lack of promotional, knowledge dissemination, policy-related and entrepreneurship activities from the umbrella and sector-specific industry associations. This has had a detrimental effect on the growth of the industry and contributed to the adoption of misguided regulatory and industrial policies by the Indian government.

The evolution of Indian medical devices saw little government and industry association involvement till 2005.

Era of weak or no representation

In post-independent India, the prevailing rates of tariff on medical devices were around 40 to 60 per cent until 1990, though 'life-saving' medical devices

could be imported duty-free (Mahal and Karan, 2009). During this period, a majority of the Indian population had very limited access to medical devices, and the market size was US\$ 280 million (Ramani & Rameseshan, 1989). The first major achievement for the Indian medical device industry was the indigenous development of the Jaipur prosthetic foot, a leg and foot made of locally available soft materials, by craftsman Ram Charan Sharma and surgeon Pramod Sethi in 1968. The co-inventors then joined the Bhagwan Mahaveer Viklang Sahayata Samiti (BMVSS), which in 1975 started offering free prostheses in India under BMVSS. This success spurred the establishment in 1976 of the Sree Chitra Tirunal Institute for Medical Sciences and Technology (SCTIMSCT), which had a biomedical technology wing dedicated to the development of medical devices. This proved significant in laying the groundwork for the future development of the Indian medical device industry.

During this period, there was an absence of large-scale collective action and therefore, lack of serious representation of the medical devices industry through associations. Having said that, we should note that small-scale collective action had just started to emerge and therefore different segments of the industry began to be represented by some industry associations.

These included the Medical Disposables Manufacturers Association (1990), Medical Surgical and Healthcare Industry Trade Association, and All India Plastics Manufacturers' Association. However, these sub-segment associations represented the narrow agendas of their industries, suffering from a lack of leadership and lack of representation for all segments of the medical device industry under one roof. Meanwhile, MNCs were dominating the domestic market in all critical areas and were primarily involved in the distribution of medical devices. In the absence of research infrastructure and well-trained human resources, MNCs entered the domestic market either by employing local agents as distributors of products or setting up sales and distribution presence rather than setting up local manufacturing plants.

After economic liberalisation in the 1990s, the increasing size of the healthcare market gave a boost to domestic firms and also led to increased imports. The Indian government significantly reduced import tariffs on medical devices to the range of 15 to 30 per cent and de-licensed imports. Growing between 15 and 20 per cent a year in the 1990s, India's market for medical devices reached \$680 mn in 1995 (Kader & Priestly, 1997). In 1995 more than 90 local firms were prominent, with 22 dominating production, joint ventures and collaboration with overseas firms. There was a significant increase in imports, though this did not resolve issues of access, affordability and appropriateness.

By the year 2000, the Indian healthcare market was growing at 15% CAGR and the medical equipment market at 17% per annum (Kamath, 2010). However, the absence of large-scale representation through industry associations with

special interests in medical device and the consequent lack of communication between industry and policymakers led to the development of Indian industrial policies that indirectly rewarded imports rather than innovation of domestic manufacturing firms. It also resulted in regulatory neglect of the industry by the Indian government. Most devices were sold without any monitoring by a regulatory authority, and this lack of oversight opened the door for low-quality devices to enter the market and weakened Indian manufacturers' capacity to export following international standards. The small size of the domestic industry, the diverse nature of products, and the absence of strong industrial leadership resulted in the neglect of the medical devices industry from any umbrella or apex industry associations. To put it another way, there was not intermediation between domestic industry of medical devices and government in the Indian innovation system. The issue of regulation came to the forefront in 2005. The government-owned hospital in Mumbai used an unapproved drug-eluting stent on patients and 60 were harmed. Taking cognisance of this issue, the High Court ordered the Indian government to frame standards for medical devices sold in India. The Indian government then brought 10 medical devices under the jurisdiction of the Drugs and Cosmetics Act, 1940. However, it became evident that the regulatory framework and infrastructure designed to govern pharmaceutical and cosmetic products were totally inadequate for governing medical devices due to the difference in products, their use in the human body and packaging. This proved to be the catalyst for government-industry linkages in the medical devices industry.

Sprouts of representation

The advent of new medical device regulation and growth in healthcare spending shifted focus onto the operations of domestic firms and led to the formation of the Medical Device Equipment division in umbrella industry associations. For example, CII formed the National Committee on Healthcare and CII Medical Equipment Division to provide a nodal point of reference for the industry, a forum for dialogue with the customers & government, and an appropriate regulatory structure. However, the lack of a sector-specific industry association became apparent in 2005 when the Indian government categorised medical devices as drugs and put them under the Drugs and Cosmetic law. This spurred health industry associations into action for representing the interests of medical devices manufactures in India. CII launched the 1st Indian Medical Technology Conference in 2007 as a platform for bringing policymakers, domestic firms and MNCs together to identify the needs and promote the interests of the Indian industry and discuss the way forward. CII has established this as an annual event and brought in Deloitte, a consultancy firm, as a knowledge partner. Subsequently, the limited representation by the umbrella organisations such as CII and FICCI, and their

positions on import duties and economic liberalisation led to the formation of two sector-specific industry organisations focused on diagnostic and medical device industries, in 2009 and 2015, respectively. In 2002, around 19 diagnostic manufacturers – both Indian and MNCs – came together to form the Association of Diagnostic Manufacturers of India (ADMI). The main objective of this association was to educate the government (state as well as central) about the difficulties and bottlenecks faced by the diagnostics industry with a view to ensuring the healthy growth of this industry. ADMI undertook knowledge dissemination activities in the form of workshops with experts on IPR-related issues and GMP manufacturing practices. It also pushed for a uniform VAT tariff for diagnostics throughout the country, on a par with that applicable to drugs and medicines. By 2005 similar promotional initiatives were being undertaken by other umbrella industry associations.

In 2009 the Association of Indian Medical Devices (AiMED) was established as a forum to cover key issues facing Indian device manufacturers in the absence of an effective regulatory framework. Mr V. Agarwal from M/s Surgiwear, a conveyor for AiMED comments, the industry needed to create a forum to cover common issues of the stakeholders. So, we all decided to form an umbrella association of Indian Manufacturers of Medical Devices covering all types of consumables, disposables, equipment or diagnostics. AIMED will provide a larger and more powerful single platform when needed (AiMED, website)

Representing the interest of medical device manufacturers, AiMED looked to emerge as a single point of contact to the government on matters of the medical device industry, advocacy, information and educational service provided to its members and lobby for funding from the government.

The emergence of multiple associations with different sets of agenda

Post-2010, the increasing disposable income, poor health infrastructure, the emergence of private health insurance and public-private partnerships, along with the shift towards hospital-based tertiary care, led to the emergence of the healthcare industry as an attractive area of investment for international capital. This increasing focus and significance of the medical device industries saw the emergence of multiple associations representing the interest of their members (table 3). For example, the Medical Technology Association of India (MTAI) was established in 2015 by MNCs operating in India to strengthen their voice in increasingly chaotic fields, while the All India Syringes and Needles Manufacturers Association (AISNMA) emerged as a nodal association for domestic syringe manufacturers in India and has 19 members located across the country. Mr Rajiv Nath founder of AiMED and president of AISNMA, emerged as a strong voice of domestic medical device manufacturers.

Table 3 Key organisations representing the Indian medical device industries.

Sector	Sector specific	Umbrella industry association
Medical devices	Association of Diagnostics Manufacturers of India (ADMI) (2002) Association of Medical Devices Industry (AiMED) (2007) Medical Technology Association of India (MTaI)(2013) All India Syringes and Needles Manufacturers Association (AISNMA) Association of Diagnostic Manufacturers of India (ADMI)(2002)	Federation of Indian Chambers of Commerce and Industry (FICCI), Confederation of Indian Industries (CII), ASSOCHAM (Associated Chambers of Commerce and Industry of India)

The concerted effort by different industrial organisations forced the Indian government to form the Indian Medical Device Regulatory Review Group as a forum for the regulated/unregulated industry, the regulator, the conformity assessment bodies, the testing institutions, and consumer groups with a view to bringing in overdue reforms. AiMED, along with other industry associations, made a strong representation on this forum, and this led to the framing of specific regulations for the medical devices industry in 2014.

If issues of regulation brought these associations together, then issues of industrial policy led to divisions between industry associations. The Indian government continued to reduce import duties, eventually to 12.5 per cent by 2004. By 2013 custom duty on medical devices was charged at a uniform rate of 5 per cent with the countervailing duty of 4 per cent and with complete exemption from special additional duty. This led to a sharp increase in both the volume and the value of imports. In 2014, the Indian government opened the medical device sector for 100 per cent foreign direct investment as an incentive for MNCs to set up a manufacturing base in India, intensifying competition within the sectoral innovation system. Domestic manufactories had to upgrade their innovative capabilities in order to compete with MNCs. CII, along with other umbrella associations, favoured this policy move by the government. In contrast, AiMED argued that this would harm the interests of domestic manufacturers. These contestations were further compounded in 2015 by MTaI that took a similar position as CII in supporting the opening of the medical sector to 100% FDI and argued against the AiMED position of protecting the domestic industry. There were other areas of significant disagreements, such as the exemption for medical devices from GST (Goods and Sales tax), self-regulation, import restrictions, price controls and export restrictions during the

covid pandemic, between various industry associations representing the medical device industry. This divergence of industry voices has worked against the development of coherent industrial and trade policies in the Indian medical device sector.

This is not surprising since the logic of collective action requires associations with collective interests to put joint pressure across the government for the supply of collective goods.

6. Analysis and discussion

Table 4 presents the different activities undertaken by the industry associations in the medical device industries.

Table 4 Industry associations' key activities in support of the medical device industry

Nature of activity	Year	Description of the activity	Name of the associations
Knowledge dissemination activities	2009	Workshop on FDA and CDRH regulations for medical devices National conference on medical devices moving up the value chain	FICCI
	2010	National workshop on medical device regulations in India 2nd workshop on USFDA and CDRH regulations for medical devices	
	2014	FICCI - AERB Awareness program on Radiation safety & quality assurance	
	2015	Global Medical Electronics & Devices Conference: Medical Technology - Key Enabler to 'Swastha Bharat'	
Industry promotion activities	2008	Organisation of annual 'Medical Technology Conference'	CII
	2011	Launch of FICCI-Deloitte Thought Paper titled "Indian Medical Electronics Industry-Outlook 2020"	FICCI
		Launch of FICCI-Frost & Sullivan Report titled "Assessment of Factors determining Accessibility of Medical Devices in India"	
		Indian Medical device Summit	ASSOCHAM
	2022	14 th MedTech Global Summit	CII
Regulatory, trade and industrial policy related activities	2009	Roundtable discussion with Minister for Health and Family Welfare	FICCI
		Regulatory reform and initiates the formation of Indian Medical Device Regulatory Review Group Abolishment of exemption from custom duty for 111 items to protect domestic industry	AiMED
	2010	Vision for Medical Electronics a Road for Opportunities and Inclusive Benefits" for Ministry of Health and Welfare	FICCI
	2012	Changes in excise duty specified raw materials used for medical device industry Setting up of separate department for Medical Devices to attract investors	AiMED
	2013	FICCI roundtable on challenges and opportunities in the medical device sector in India	FICCI
	2014	Consultative Meeting of IVD Industry Stakeholders	FICCI
	2017	Workshop on Indian Certification of Medical Devices Scheme (ICMED) and Medical Device Regulation (MDR)	AiMED
	2018	India-Japan Medical Products Regulatory Symposium "Pharmaceuticals & Medical Devices"	FICCI

Building policy literacy: Competing interests and contesting policy positions

It has been well established that the industry associations primarily work to represent and protect the interests of their members through lobbying with the government, which can be detrimental to the progress of the sector. The Indian medical device industry is much smaller in size compared to pharma-biotech and is mainly dominated by MNCs with interests in imports than local production, which has emerged as the cause of intra-association conflict. These competing interests do reduce the impact of associations rather than their absence and create conditions that can stifle innovation. It is evident in the stance taken by these associations on exemptions of medical devices from GST, import restrictions and self-regulation proposals. In the case of medical devices, the lack of coherent positions on issues of industrial and trade policy is clearly reducing the bargaining power of industry associations in the emerging new scenarios. However, this contestation does bring some positive outcomes. Banda et al., (2021) point out that contestations among associations contribute to policy literacy, learning and problem-solving agility among Indian policy- and decision-makers. They further argue that the resulting policy literacy and learning provided scope for challenging discussions and serious engagement from a diverse set of stakeholders about how institutions should be built. It is also evident in the case of the Indian medical device industry. The emergence of these multiple associations in the Indian medical device industry allows representations of various interest groups such as small firms, overseas multinational corporations (MNCs), local MNCs and sub-segments. These associations are putting forward policy positions using data and consultancy reports and playing a key intermediary role by ensuring communication between small and medium firms, local MNCs and overseas firms, and representing their views to the government. The contestation among them restricts their roles as drivers of the government policy, but 'noisy' debate helps to develop policy literacy and consensus-building abilities among Indian policy-makers

Towards collaborative action: From lobbying to strategic partnerships for innovation and development

Kale and Wield (2020) highlight that the lack of collaborative action among key stakeholders prevents the growth of the industry. However, the emergence of multiple sector-specific associations and strong interests from umbrella associations are plugging this gap. These associations have identified some areas of common interest that are critical for the development of industry and play an influential role in forming networks and creating linkages among different stakeholders to achieve those objectives. For example, these associations are now part of the National Medical Device Promotion Council (NMDPC) set by the Indian government in 2020 to develop local industries and attract FDI in the sector. The other objective of NMDPC also includes building

synergies among various departments in view of the diversity and multi-disciplinary nature of the sector to harness the potential of the Indian MedTech sector. The second example of collaborative action and strategic partnership for innovation and development is evident in their actions during the covid-19 pandemic. Banda et al., (2021) show that industry associations brought together start-ups and smaller firms with larger manufacturers to produce ventilators and protective equipment. Thus, industry associations can act as brokers or intermediary institutions to facilitate knowledge renewal and promote linkages between critical sectors and can signal through policy debate where different sectors' interactions are increasingly important.

The importance of government support

Early government support for the nascent Indian medical device industry simply did not exist. The most credible explanation for this is that medical devices were not viewed by the Indian government as building upon India's competitive advantage in pharmaceuticals and healthcare-related industries, nor building upon India's S&T infrastructure in the life sciences. The early exclusion of medical devices from the Indian government's innovation policies is due to the low-tech nature of most Indian-produced medical devices at the time, coupled with a lack of knowledge and understanding of the importance and potential of an emerging Indian medical devices industry. Without initial government interest and thus support, the nascent Indian medical device industry was unable to consolidate its interests in a way that would allow the early emergence of industry associations, associations that could then articulate the relevance, interests and needs of the medical device industry to the Indian government. Further, the government will need to find ways to establish and support local cross-sectoral industrial clusters that are a critical part of medical device industries to sustain local learning and capabilities. Banda et al., (2021) observe that it can be a challenge for particular sub-sectors to preserve knowledge accumulation that is based on cross-sectoral collaboration since some collaborations will be transactional and may not continue once a crisis has passed.

7. Conclusions

This paper has focused on the politics of health, unpacking the role and potential of industry associations in India as key intermediaries in the health innovation system. It has specifically explored why and under what circumstances industry associations historically emerged to represent the medical device sector and became effective in shaping government regulations.

Highlighting the importance of industry associations for the growth and development of technological capabilities in the Indian medical device sector, this paper has argued that intermediaries, through processes of closing

knowledge gaps between industry and government, facilitate institutional capacity building while shaping regulation and subsequent industry development.

The research also shows the interaction between key individuals through which complementary organisational and institutional capacities first emerge. This is particularly pertinent in developing countries where Sen (2016) suggests 'deals' culture has more primacy than 'rules'-based ways of working. It further reinforces the work of Reveley and Ville (2010), which argues that effective associations are those that can accrue and apply considerable social capital to successfully engage with and influence, over time, changing the industry and regulatory environments.

In healthcare industries, policymakers struggle to grasp the complexity of change required to bridge the gap between existing institutions and those required to promote growth and capability development. This paper emphasised the beneficial influence of industry associations acting as a mediator in the innovation system, bridging system gaps and playing a key role in shaping IPR legislation and regulatory frameworks. The government lacked the capacity to build such frameworks on its own. Industry associations emerged as an important source of ideas for regulations. In the case of medical devices, the absence of industry associations resulted in filling the gap with wrong regulations and inappropriate trade and industrial policies. This suggests that industry associations should make links with socially and spatially different stakeholders, engage with powerful institutions and harmonize different values (Lawrence & Hardy, 1999)

It is evident from this research that the evolutionary development of the Indian medical device industry in a way that builds its globally competitive innovation capacities while effectively addressing its local healthcare needs will require greater trust and transparency and more complementary relations between industry and government. Policy creation and implementation are complex because it is inherently political and therefore controversial. To achieve industrial development among the conflicting perspectives and interests of various institutions and organisations, industry associations will have to embrace a partnering approach by aligning the interests of their members with the wider healthcare objectives of the country. There are important lessons here for other sectors in India and for developing countries beyond India.

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Steering the wheel to deliver what? Capacities, innovation, and coalitions in the biologics sector in latin america

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Would you tell me, please, which way I ought to go from here?" "That depends a good deal on where you want to get to," said the Cat.

- 'Alice's Adventures in Wonderland' by Lewis Carroll, 1865.

1. Introduction

COVID-19 was declared by the World Health Organization (WHO) as a public health emergency of international concern on January 30, 2020. While it challenged the capacity of all states to fulfill their role in ensuring their citizen's health, in developing countries, amidst scenarios of limited resources and inequalities it revealed the level of preparedness held by each country to face the threat.

The pandemic also highlighted the global dispute over access to supplies and medicines, demonstrating the need to strengthen national innovation systems. As the pandemic progressed, access to biological products (diagnostic reagents, biotherapeutics, and, especially, vaccines) to deal with COVID became a critical issue for national health authorities. Public procurement of these biological products in Latin America, mostly imported from developed countries, strained health budgets and balances of payments, making access to critical health supplies difficult. The pandemic made even more evident the relevance of investing in health -understood as a constitutional right- and of strengthening the capacities of the National Science, Technology, and Innovation (STI) Systems to develop key products and inputs to face epidemic diseases, according to the needs of each country.

This paper aims to analyze the working and delivery capacity of Sectoral Innovation Systems (SSI) in biologics in Latin America, taking the cases of Argentina, Brazil, and Colombia. How are the different national sectoral systems in biologics shaped? What elements determine each national trajectory, where are they oriented and what does each one seek to deliver? How do STI and health policies interact with other policy subsystems?

By comparing three national trajectories of sectoral systems of research, technological development, and innovation in biological products, we seek to understand innovation strategies in the health sector as a result of the tension between available capacities (scientific-technological, productive, health and regulatory), the coalitions of interests involved and positions taken on policy preferences (not necessarily related to the health sector). It shows how the functioning and delivery capacity of biological products by these systems depend on coalitions of business, social, and state actors that sustain the status quo in each country and how these coalitions condition possible future trajectories.

In theoretical terms, this paper aims to incorporate a political economy perspective of Sectoral Systems of Innovation (SSI). The cross-case comparison shows that innovation does not necessarily emerge as the primary goal of such systems in a unidirectional approach to capacity building. It shows the diversity of directionalities that these trajectories can assume, discursively oriented to build capacities to supply the health system, through a set of alternatives that are co-produced (transformed and reinforced) with political commitments, country visions, and broader policy objectives.

The paper is organized as follows. In section 2, we present a conceptual analysis of the components and trajectories of SSI, discussing the literature in terms of the directionality of its delivery. In the third section, we describe the performance of the three SSI using selected indicators. In the fourth section, we discuss comparative profiles of these systems, highlighting their distinctive features and ordering them according to the dimensions introduced in section 2 and 3. Finally, we conduct a cross-case comparison, systematizing the main features of each case, building on three profiles of the SSI in biologics that give count of each country's historical trajectories, power coalitions and conflicting policy choices.

2. Sectoral systems of innovation: Where to?

The literature on sectoral systems of innovation and its subsequent developments (Malerba, 2002; 2005; Malerba and Nelson, 2009; Malerba and Mani, 2009) serves as a conceptual starting point for understanding the differential capabilities in sectoral innovation systems and the efforts required for innovating, developing, manufacturing, and adopting biological products. This systemic framework allows to analyze how knowledge, technologies, and

health capabilities are embedded in a complex ensemble of relationships. It involves the multiple actors involved (social and productive, governmental, regulatory, environmental, and educational) as well as the fabric of linkages between them, market and non-market relations, learning processes, regulations, public and private efforts in R&D and innovation, and the processes of manufacturing and adoption of products and services (Natera, Tomassini and Vera-Cruz, 2019; Hanlin and Holm Andersen, 2019).

Adopting a systemic perspective in the health sector deems relevant for two reasons. Firstly, innovation activities in health are widely diverse, involving a large set and nature of heterogeneous actors: hospitals and clinics, universities and R&D centers, private and public companies providing final goods and industrial inputs, different regulatory agencies, funding agencies, venture capital, accelerators and incubators, physicians and biochemists, clinical analysis laboratories, patients and users, health agents, public and private health insurances, contract research organizations, government agencies (health, S&T, industry, trade, finance), international organizations, trade unions, technical and professional associations, among many others. Secondly, it is necessary to understand innovation, knowledge transfer and application as interactive and collaborative processes between these different actors - from the scientific system, providers and the private sector - taking into account local specificities. The inclusion of different social actors, as well as the strengthening of organizational and institutional learning among the different agents and components of the national STI system and the health sector is key to the success of STI developments in the health sector.

Having 'healthy' health innovation systems (Natera and Tommassini, 2019), namely, a virtuous dynamic where knowledge production and innovation efforts translate into improvements in health, presents a set of recurrent obstacles, that have been widely addressed by the innovation in the health sector literature: (a) the linear visions on the innovative process, that assume that investment in basic research will necessarily lead to new technologies and their adoption by health systems underestimating the complexity of translating health research into industrial processes and into the clinic; (b) the disconnection between STI policies for the health sector and the requirements and constraints of the industrial sector, simplifying the transition from laboratory-level developments to the generation of useful applications (underestimating the scientific and technological capabilities required for this); (c) neglecting the complexities of regulatory systems and procedures in the design of innovation policies and processes that are specific for each type of application (vaccines, treatments, diagnostics, biological inputs, etc.); (d) the limited inclusion of the public sector, without considering its agency on the research agenda, purchasing power, adoption, strengthening of health care and logistics. Intermediate activities, contextual variables, and additional capabilities or infrastructures needed to incorporate new knowledge and

applications into healthcare practice are also often not incorporated; (e) disconnection between innovation policy actors and agencies and health policy arenas.

From the standpoint of STI policies and R&D, these obstacles account, among other things, for the lack of coordination in actor interactions, policy design, regulatory systems, and the applications of scientific knowledge for the health sector. Social studies of biotechnology have shown how this manifests in two main gaps: (i) between biomedical research and its translation into technological applications and (ii) between the design of devices and technological prototypes and their effective production at scale, adoption, and use in the framework of clinical practice, public policies, and health services (Kreimer and Zabala, 2006; Bortz and Thomas, 2019). This trend has been characterized as “applicable not applied knowledge”, a critical feature of semiperipheral countries knowledge production (Kreimer and Thomas, 2001; Rodriguez Medina et al, 2019). The flip side of this trend are phenomena such as “cognitive exploitation” (Zukerfeld, 2017) and “blind technology transfer” (Codner & Perrotta, 2018). This depicts a double-coined scenario, where here the biomedical agendas in the South become determined by leading academic institutions but also by large pharmaceutical companies and the knowledge produced in these peripheries becomes appropriated by international industries, and not capitalized locally (Carrillo et al, 2022).

In particular, as biologics comprise a whole set of interrelated products (biopharmaceuticals, vaccines, diagnostics, production inputs), the SSI provides a helpful grid to organize the main elements that shape the form, structure, and organizational dynamics. This involved mapping (a) the actors, networks, and interactions, heterogeneous agents (whether individual or organizational, firms, R&D units, and other organizations) that acquire, produce, and use knowledge, and the linkages among them for knowledge creation, transfer, and development. Second, (b) the institutions, understood as the set of rules, routines, established practices, and regulations within which both the cognitive actions and interactions of the actors are embedded and configured. In each case, the form and dynamics of the regulatory framework becomes coproduced with each country’s sectorial trajectory and shape in turn innovation pathways for the biological sector. Third, (c) the knowledge, learning processes, and technology, which constitute the cognitive basis of the SSI, are in turn a by-product and a conditioning basis for these paths. These may have different degrees of accessibility for agents, opportunity, and accumulability. As we will show, for the biologics sector this not only requires disciplinarian life sciences knowledge but also complementary capabilities for product development and approval that remain less explored.

According to the theory, knowledge changes in two different ways: cumulatively, usually by dominant companies, and drastically, which requires new competencies for innovation and can bring about a change in the market

structure. At the same time, it states that changes in demand, users, and suppliers can modify the environment in which companies operate, favoring some activities and firms over others. The performance of a particular sectoral system (or subsystem) of innovation and the changes it undergoes over time is the result of the interactions and interconnections between the different elements of the sectoral system.

However, beyond mapping the system and its components, the problems posed by the health innovation systems, challenged by the evidence collected during the first stage of the fieldwork conducted for this work deemed insufficient to understand three key points: (a) the *functionality* of the system (how and why does the SSI work as it does?); (b) the *directionality* of the system (where is the system oriented to? What pathway has been followed by each country?) (Stirling, 2009; Leach et al, 2010; Frost et al, 2019); (c) the political economy of the system (why the system functions and orients itself in these directions? What coalitions of actors and material elements influence its orientation and how does the functionality of the system reinforce these power coalitions?) (Shadlen, 2017).

As does most of the innovation system's literature, the SSI framework includes as its underlying assumptions: (a) the need to gear the systemic elements towards innovation as a desirable goal by itself and (b) that innovation through capacity accumulation will lead to growth, development and assuring access to health goods. In the past 3 decades, innovation became a dominant cultural value and policy imperative (Pfotenhauer et al, 2019), "assumed as the key ingredient of any effort to improve people's quality of life, essential for addressing some of society's most pressing issues, such as climate change, health and poverty" (OECD, 2010). However, how these innovation paths are led, which actors take the lead in "stirring the wheel" towards certain desirable goals (whether it is competitiveness for economic growth, achieving sustainable futures, or social inclusion), and how they negotiate these pathways have been less explored.

The adoption of innovation systems in Latin America since the 1990s has been widely studied. Latin American STI scholarship has also analyzed its historical trend for the adoption of external models, institutions, and instruments - sometimes in an acritical manner via imitative strategies (Albornoz, 1997), some others through local re-elaborations of these institutional models (Aristimuño et al, 2017).

Regional literature has shown that there are no practices and policies that can be extrapolated from one country to another with guaranteed success (Thomas & Dagnino 2005). In that vein, what deems interesting is highlighting the diversity of the systems and their differential capacities, as a result of the trajectories on which they were formed. These are the result of an implicit or explicit balance of priority objectives, which should result from a process of

negotiation and agreement between public and private stakeholders (Shadlen, 2017). Beyond innovation as a means by itself, innovation systems address multiple and sometimes divergent objectives and priorities and there is no single measure of successful performance. Different systems are more or less effective in meeting different objectives, which often come into tension.

In this scenario, the problem of directionality and alignment of knowledge and innovation production efforts -especially those oriented towards inclusive development objectives- became a focus of concern (Leach et al 2010; Schot and Steinmueller, 2016; Chataway et al 2019). While there is strong evidence of the power of innovation to generate economic growth in competitive global economies in particular sectors, there is less evidence on how the benefits (and sometimes the risks) are distributed. In this vein, it is argued that building innovative capacities in health leads to better access in line with general spillover economic development models. But little is known about how to direct them to foster more equitable societies (Leach et al, 2010; Frost et al 2020). The problem of directionality refers thus to the technical, social, and political objectives and aspirations for transformation that guide policy, science, and innovation (Leach et al, 2012). Ultimately it answers the question: knowledge and innovation for what? (what kind of knowledge is brought into play, in what innovative trajectories, and with which purposes). This question is not trivial and goes beyond the prioritization of a specific strategic sector or technology: it requires thinking about the particular strategies of change being pursued: the scale, centralized or distributed governance, medium or long term, capital intensive or not, innovative strategies, privileged actors, etc. Particularly, in the health sector, the different policy subsystems may prioritize issues such as access to medicines, technological innovation, strengthening local companies, attracting FDI, generating exports, or creating globally relevant startups. Promoting some of them often implies sacrificing or giving less relevance to others. This also implies favoring some actors over others. Acknowledging this divergence of possible objectives, and the role that different agencies, institutions and public and private sector actors play in pushing the various agendas, and the capacities they need to do so, is therefore a fundamental first step in establishing a policy to support the bio-based sector that will have concrete impacts.

On this matter, institutions, and regulations constitute a central component of these material matrices in which the visions of directionality and desired futures work: they shape technological development, research, and innovation trajectories towards those directions that are considered 'good', 'desirable' and/or 'possible' (Therborn, 1999). Regulatory shaping -in its broad sense- involves a power exercise, where a multiplicity of actors and elements (technologies, institutions, funding, guidelines, knowledge, ideas, and beliefs) intervene, negotiating materials and technological practices, in an attempt to align them with desired paths of technological development and governance.

These regulations, as an attempt 'to shape the governance of technology in order to promote the public interest' (van Zwanenberg, Ely and Smith, 2011:12), in turn, organize spaces, social relations and actors' behaviors; condition structures of social distribution, production costs, access to goods and services; and generate incentives and restrictions through the distribution of benefits and sanctions, seeking to build irreversibility on the status quo (or revert it) (Callon, 2001; Lascoumes and Le Gales, 2007; Bortz, Rosemann and Vasen, 2019).

Thus, the political economy of STI policies involves these critical decisions of sanctions and rewards, which generate lock-in effects along paths that are difficult to reverse, elevating the barriers and costs of endeavoring alternative development trajectories. Here regulation is not only understood as an exercise of control on established technology products, processes, and practices but also as the aspiration to direct the development of new technologies. It seeks to ensure that technologies, and the social practices through which they are produced and used, follow one orientation instead of others, stabilizing them in that direction (van Zwanenberg et al., 2011). Third, regulations tend to be presented as serving 'the public interest', balancing private interests according to certain collectively agreed principles. As public policies are aimed at 'providing', 'distributing' and 'regulating' (Braithwaite et al, 2007), 'public interest' is considered a contested political ground, whose definition results from negotiations between diverse actors to impose their interpretations of what is 'good', 'desirable' and 'possible' (Therborn, 1989). In the case of the STI policy subset, as regulations shape behavior, they also contribute to the ways in which technology development pathways unfold, sending signals (sanctions and rewards) about desirable/undesirable, acceptable/unacceptable directions of technology development and use. At the same time, STI policies tend to be seen as 'distributing' and 'providing' activities (i.e. the distribution/provision of human resources training, subsidizing public, private, and public-private projects, acquiring infrastructure). Thus, technology regulation not only shapes the ways in which technologies are used, and how and to whom access is provided, but also may influence decisions on state innovation priorities, public and private investment, and market structure, among others.

Thus, directionality also affects the distribution of the benefits and affects the processes of knowledge production and use. Usually, these questions have remained open and out of the discussion, guided by the general imperatives of growth or progress implicit in the prevailing normative models that drove the science and innovation systems. Orienting them toward inclusive and sustainable development, or towards or -even in more modest terms- and equitable access to goods and services, in this case, to meet access to health as citizen rights, requires bringing to light what has historically been presented as implicit bias, in order to actively steer them toward the desired types of transformation. In particular, in the health sector, this lead to the need to

addressing the challenges for the orientation of research and development agendas in directions required by local systems and for the scaling of productive capacities, the problems of distribution of the benefits of knowledge and innovation among the various actors of the system, and how these priorities become negotiated.

3. Materials and methods

This paper is based on a qualitative methodology for a comparative cross-country analysis of the biological product subsector in Argentina, Brazil, and Colombia. We aimed to take up the segment of biological products as a whole, including in its survey of existing subsystems for therapeutic products (including biopharmaceutical drugs and advanced therapies), serum and blood products, vaccines, diagnostic reagents, and inputs for the manufacture of biologics (e.g. fetal bovine serum partitioners, RNA sequences, functional proteins, albumins). This decision responds to an attempt to capture the linkages between traditional and biotechnological biologicals, the increased interconnections among those capacities, and the need to understand the nuances of their working, especially after COVID-19, within each country's health system.

Research departed from an exhaustive analysis of secondary sources, reviewing and analyzing indicators to characterize the status and transformation of the health sector -its scope, directionality, and coverage- and of the sectoral system for the R&D and manufacturing of biologics. We surveyed: systemic inputs (STI investment and specifically in the health sector, health budget, S&T human resources training, etc.); relevant actors and institutions; knowledge production and innovation in the health sector and its results materialized in articles and patents; relevant regulatory frameworks, both related to the validation and approval of diagnostic reagents, clinical trials, therapeutic products, and vaccines, and those related to intellectual property rights. Data was also surveyed to understand the structure and operation of the most important markets for biological by-products, including each market's absorption capacities.

To that end, data was retrieved, systematized, and analyzed from WHO/PAHO, Health, and Economy Ministries, comparative STI databases (e.g. RICYT), national S&T databases and repositories (e.g. Lattes in Brazil, SICyTAR in Argentina, S&T Observatory in Colombia), governmental open data initiatives, patent databases (UPSTO, PATENTSCOPE, Patent Inspiration). Information on markets and firms was retrieved from UN Comtrade and from national biotechnology and pharmaceutical chambers. This helped outline the general features of diverse Latin American countries and the pathways undertaken by their biologics sector.

In a second step, a set of 22 semistructured interviews were conducted between September and November 2020: Argentina (5 specific interviews, drawing from a previous background in the sector that led the authors to conduct over 70 interviews held for previous projects), Brazil (8 interviews), Colombia (5 interviews). Even when it was not a part of the study, 4 additional interviews were conducted in Peru, at the moment the country was dealing with conflicting choices on how to promote and where to direct its biological sector. The challenges posed by Peru, with an early stage trajectory in this sector, became insightful to pose the questions on how each country negotiated conflicting policy choices and shaped their trajectory according to diverse expectations on what is it for the system to deliver, the power balance between different actors and -also from that- how these policies interacted with other policy subsets.

For the interviews, we selected key informants, scientists, entrepreneurs, actors in health regulatory agencies, regulatory consultants, IP specialists, public officers in National Health Institutes and Science and Technology governmental agencies, and directives at corporate chambers and associations. This aimed to cover the diversity of the biologics sector (therapeutics, vaccines, diagnostic reagents, industrial inputs) and also the diverse areas of public and private action on the matter (R&D, manufacturing, IP and health regulation, S&T, and health policies). Each interview was conducted by a two-researcher team, transcribed and codified to capture the working of each country's SSI, the dynamics of regulatory and technical aspects and institutional capacities, mapping regulatory, technical, governance, and institutional capacity changes and, with that, capturing the emergents of their political economy and directionality.

To organize the comparative analysis of the biologics systems, we distinguished three types of capabilities (productive, S&T and health) and two types of desirable attributes (interministerial coordination and stakeholder linkages). These capacities and attributes appear as necessary and complementary support bases in the trajectories of the systems in each of the cases analyzed. Although they could be separate dimensions, state institutional capacities cut across and are a necessary component of each of these dimensions:

(a) *Industrial capacities of the pharmaceutical sector.* By productive capacities, we refer to the base of pharmaceutical companies and the local capacity for drugs, vaccines, reagents, and inputs manufacturing (in that order of relevance). The domestic pharmaceutical industry is important since biologics innovation systems are often strengthened through the investments that pharmaceutical companies make in research and development of biologics, which is illustrated by the Argentinean case. The cases show that the formation of a strong national pharmaceutical sector is a consequence of proactive policies to promote them, which took different forms in different historical periods, and of permissive

intellectual property rights that enabled growth through the copying of products and inputs developed in leading countries. This strategy seems difficult to implement today, especially for countries with restrictive trade agreements (e.g. Peru and Colombia). However, even with today's more restrictive intellectual property laws, there are opportunities to access technological knowledge developed by companies in other countries that should be explored. Likewise, countries can resort to a series of instruments of productive development policies, STI policies, and novel trade protection to strengthen productive capacities under present conditions.

(b) *Scientific capabilities.* Biotechnology activity was characterized from its origins by the synergy between science and industry (Owen-Smith et al., 2002; Zucker et al., 1998; Arora and Gambardella, 1994). Biotechnology companies feed on the results obtained in the scientific field and "transform" them into commercial products. The preponderance of such collaborations highlights the importance of a local scientific base for both the emergence and subsequent development of science-intensive companies. Universities and research centers are one of the most relevant sources for the innovative activity of companies in this sector (Cohen et al., 2002; Arundel and Geuna, 2004; Kaufmann and Todtling, 2001). They contribute to accelerating innovation processes (Mansfield, 1991; Klevorick et al., 1995) and to strengthening the scientific capabilities of firms (Arora and Gambardella, 1994) by providing knowledge that is not available, or at least is more difficult to obtain, in industry. To assess scientific and technological capabilities in areas such as health, biosciences, molecular biology, and biotechnology, we surveyed the level of public and private investment in R&D, scientific institutions, universities, and the number of teams of scientists and engineers working in these areas, and we will analyze their role in the performance of innovation systems.

(c) *Health capabilities.* We refer by this to the capacity of the health system and health policies to drive the demand and production of medicines and vaccines in a coordinated manner. These capacities depend on the level of public spending on health, public procurement policies for medicines and vaccines, and national vaccination programs, among others. For the development of these policies, the Ministry of Health plays a fundamental role in coordinating health objectives with those of local drug development and production. Public spending on health, public purchasing policies for drugs and vaccines, national vaccination programs and the role of the Ministry of Health in coordinating health objectives with drug development and production can have an important impact on the performance of the sectoral system of innovation and production of biological products. We call these types of resources health capacities. Of the cases analyzed, the case of Brazil illustrates how the Ministry of Health can take a leading role in the innovation system, being Brazil is the country of our sample that best exploits these capabilities.

(d) *Inter-ministerial coordination.* Recognizing that the systems involve multiple objectives across several ministries, an attribute for the development of the sector is its capacity for effective coordination of policies and regulations at the inter-ministerial level. To address both the promotion of the sector and the health care of the population, the biological sector system requires the construction of institutions capable of coordinating policies among three levels: STI, productive, and health. The different agencies, regulations, and actors have to be aligned on the objectives and priorities previously established in these policies. This coordination requires a fluid dialogue between public and private actors and the different agencies involved in these areas. Without this coordination, it seems very difficult to resolve the tensions between health and production objectives. This coordination must take into account the impact of the regulatory framework in terms of intellectual property and the evaluation and approval of biological products, which again may have multiple objectives with divergent effects on the different policy objectives and the subsectors involved.

(e) *Linkages and interrelatedness.* The second desirable attribute is the quality of the linkages between the different segments or actors of the sectoral system, particularly between actors focused on developing scientific knowledge and industrial manufacturing. In the field of biotechnology, the complexity of the technology and the high risk involved in the development of new products and processes, coupled with the rapid pace of technological change and the generation of new knowledge, require firms to interact and exchange knowledge and resources with other actors both inside and outside the industry itself. Empirical evidence from leading countries, such as the United States or European countries, clearly shows that the development of biotechnology activity relies on a complex cooperation ensemble between different types of actors: companies, universities, public regulatory and technological research institutes, laboratories, and venture capital (Bartley et al., 1992; Shan et al., 1994; Koput et al., 1997; Owen-Smith and Powell, 2004; Powell et al., 1996; 2005).

It is also important to bear in mind that the results will be conditioned by the specific characteristics of each country's political economy. Industrial and innovation policy must therefore be sensitive to this. In this sense, an important dimension that should be considered, since it conditions the possibilities of development and performance of sectoral innovation systems, are the dominant coalitions and agreements associated with interest groups and the existing economic structure, since these affect the possibilities of introducing new policies and regulations, or the difficulties in doing so. When designing strategies for the systems, it is therefore necessary to take into account the coalition of actors (business, social or state) that sustains the existing system and how these coalitions condition possible future trajectories. For example, how the national medical or scientific sector will react to a change in

regulations regarding the approval of new medicines or the experiments required to test them. Or how the business and scientific sectors will react if imports of certain inputs necessary for the development of biological drugs are liberalized (or restricted). Another important dimension is the regulatory framework and legal constraints arising from the international insertion strategy, particularly trade agreements and IPR regulations. These are the result of long-term negotiation processes and are difficult to modify in the short term, through reforms or public policy instruments. Innovation systems are the result of a long-term process that in many cases included regulatory frameworks and forms of international insertion whose adoption would be difficult today (as we will see, such is the case of the development of the pharmaceutical sector in Argentina and Brazil under protectionist regimes and until the 1980s with the absence of patents). In other words, it is a question of the determinants of political autonomy to choose and implement a strategy to strengthen the innovation system.

4. The picture: Comparative performance of SSI

To analyze the performance of SSI in Argentina, Brazil and Colombia we focused first on two performance variables: companies and production data¹ and achieved innovations achieved². The data on scientific capabilities in terms of e.g. publications and researchers are considered as efforts made. At the time of the survey, 96 companies producing biotechnology applied to health were registered in Brazil, 42 in Argentina, and 2 in Colombia. If we look at the relative participation in the total number of manufacturing companies, Argentina stands out with 0.07%, followed by Brazil and Colombia with 0.03%. If we take the participation of the total number of biotechnology companies (including those dedicated to the agricultural, textile and other sectors), the difference in favor of Argentina is even greater: 0.33% against 0.08% in Brazil.

Table 1. Biotechnology manufacturing companies

	Argentina	Brasil	Colombia
Health Biotechnology Companies - Quantity	42 UBATEC (2016)	96 Alves et al (2017)	2
Health Care Biotechnology Companies - % of total manufacturing companies	0,07%	0,03%	0,03%
Biotechnology Companies - Amount	201 UBATEC (2016)	237 (CEBRAP, 2011)	-
Biotechnology Companies - % of total manufacturing companies	0,33%	0,08%	-

Source: own elaboration based on sources indicated in the table. Number of manufacturing companies by country: Argentina 61,388 (National Ministry of Productive Development; 2016), Brazil 303,066 (IBGE; 2018), Colombia 7,631 (DANE; 2019).

Another important indicator is the proportion of the domestic market for pharmaceuticals of biological origin supplied by local production. Here Argentina stands out again, with 24%, followed by Brazil with a level of less than 10%. This means that, especially in Brazil and Colombia, almost the entire market for biologics is covered by imports, mostly by multinational companies.

Table 2. Industrial capacities in the pharmaceutical sector

	Argentina	Brasil	Colombia
National firms (market share according to units sold)	68,4% (CILFA 2020)	65,3% (Moretto, 2018)	
Import penetration - Imported medicines as % of the domestic market (2016)	39,1	36,9	64,1
Export ratio	12,2	7	10,3

Source: own elaboration. Own elaboration based on data from Statista 2018 (Data 2016) - Pwc - Colombia in ANDI Report, Cifras Sector Salud. Pharmaceutical Market.

In Argentina, local companies participate in the biologics market through local production of therapeutics, reagents, and biological vaccines, while multinational laboratories do so with imported products, mainly and in an increasing proportion of biological products³. The production of biologics by national laboratories and companies in Argentina, with a history dating back to the 1980s, has had a boost in the last decade as a result of the installation of biotechnological active ingredient manufacturing plants and the growth in the production of first-generation biotechnological drugs (interferons, erythropoietin, growth hormone and others) and biosimilar monoclonal antibodies (rituximab and bevacizumab) and recombinant vaccines (CILFA 2018). Companies dedicated to the development and production of biologics, according to a recent survey by the Ministry of Science and Technology, are highly innovative, allocating 7 out of every 100 USD of their sales to R&D activities (MINCYT, 2016), which places them well above the national average R&D intensity, which is below 1%. Thus, this segment has gained increasing importance within the national pharmaceutical sector. According to the latest survey on national biotechnology companies in the human health sector in 2014, USD 261 million of a total sector sales of USD 1,097 were exclusive sales of biological products (MINCYT 2016). Part of these sales are also destined to foreign markets. According to sectoral surveys, human health companies exported biologics in 2014 for USD 120 million, mainly first-generation biotechnology products that are exported to Latin American and Asian countries (Stubrin 2019; Gutman and Lavarello 2017). The trade deficit in the biologics sector, however, has continued to increase, which accounts for the strong trend in the drug market in this direction. In 2014 biologics accounted for 14.83% of the trade deficit while in 2019 these came to account for 41.5% of

the deficit. Biologics of greater complexity, such as monoclonal antibodies, are the ones with the largest negative trade balances⁴.

In Brazil, of the total of 96 registered companies, 60 are dedicated to biotechnology applied to health, 16 to diagnostic reagents, and 20 are clinical laboratories and cell banks. As in Argentina, companies in this country have sought to move towards creative imitator trajectories (based on biosimilars), starting with local production from imported inputs. Specific changes in the regulatory framework were very important in this process. Particularly from 2010, when abbreviated pathways were considered for the approval of biosimilar drugs, with guidelines for different types of molecules, in order to facilitate the development of the local industry (Gutman and Lavarello, 2017).

A characteristic of the sector in Brazil is a clear market division: the production of recombinant proteins and drugs is in the hands of the private sector, with a strong weight of multinational companies that import the main pharmaceutical inputs, while the production of vaccines is almost exclusively in charge of two public laboratories (Ficoruz and Butantan). In the vaccine market, Brazil has reached 94% self-sufficiency through the production carried out mainly by these public laboratories, but dependence persists in biomedicines, where multinational companies account for more than 90% of the market.

In both countries, therefore, it can be said that there are emerging domestic production capacities, both public and private, in the biologics sector, but in different segments, more concentrated in vaccines in Brazil, more diversified in Argentina, with a greater weight of therapeutics and reagents. However, despite the efforts and these emerging capacities, imports and multinational companies, which in turn make few domestic developments, have a strong weight in the sector, especially in the case of Brazil, where the domestic biologics segment has a lower weight than in Argentina.

Innovation capabilities can be analyzed comparatively with patent data. Brazil is the country in the region with the highest number of patents applied for in biotechnology, with an accumulated total between 2005 and 2015 of 16,178. Of the countries selected for this study, Argentina is next with 5,618 patents, Colombia with 1,767. In this case, the countries with the lowest investment in R&D and amount of researchers, such as Colombia or Chile appear to be more efficient.

In all three countries, and especially Colombia, however, there is a high dependence on foreign developments. If we distinguish between patents applied for by residents and non-residents, of the total number of patents applied for in biotechnology between 2005 and 2015 in Brazil, 831 were applied for by residents (5.1% of the total), in Argentina 195 (3.5% of the total), in Colombia 40 (2.3% of the total). However, these data do not distinguish the percentage of biotechnology patents by sector (health, agriculture, others).

Table 3. Patents applied for in biotechnology by residents and non-residents. Cumulative 2005-2015.

<i>Applicant</i>	Brazil	Mexico	Argentina	Chile	Colombia	Peru
Residents	831	304	195	148	40	13
Non Residents	15.347	9.652	5.423	823	1.727	1.056
Total	16.178	9.956	5.618	971	1.767	1.082
Total Patents/R&D Expenditure in u\$s PPC, average 2010-2015	43	110	110	68	112	362
Total Resident Patents/R&D Expenditure in u\$s PPP, average 2010-2015	2,2	3,4	3,8	10,3	2,5	4,3
Total Patents/Rese archers (2015)*.	6,9	28,4	10,3		26,3	41,9
Total Resident Patents/Rese archers (2015)*.	0,36	0,9	0,36		0,6	0,5
<i>In %</i>						
Residents	5,1	3,1	3,5	15,2	2,3	1,2
Non Residents	94,9	96,9	96,5	84,8	97,7	98,8
Total	100,0	100,0	100,0	100,0	100,0	100,0

Source: own elaboration based on Colciencias (2019), RICYT and MCTI of Brazil.

**The number of researchers corresponds to the total number related to the field of biotechnology.*

One limitation of these statistics is that the residents may be, in addition to national companies, subsidiaries of multinational companies that made the inventions in another country and patent them in the countries analyzed to protect them. To circumvent this problem, we analyzed a database containing the biotechnology patents that have been applied for in each country with priority. Unlike measuring the total number of biotechnology patents applied for in a country, this methodological approach reduces the sample to those patents whose first application was made in one of the countries in question (Brazil, Colombia or Argentina). Subsequently, the owners of these patents can apply for their claim in other national (or regional) patent offices in other countries where they wish to be granted a patent. But the priority of application reflects better the inventions made locally and discards those patents that have been developed in other countries (or regions) and then are

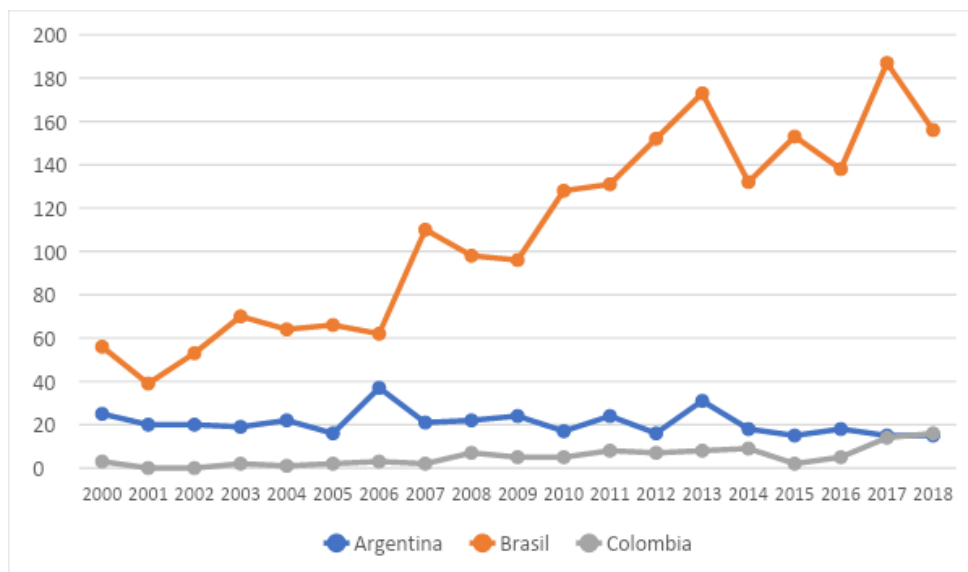
endorsed in the analyzed countries as part of strategies to protect their inventions. This shows that during the last two decades (2000-2020) Brazil led the pace of priority patenting with 2064 patents of this type, followed far behind by Argentina.

Table 4. Biotechnology patents applied for with priority (total and relative)

	Argentina	Brasil	Colombia
Total patents with priority (2000-2018)	395	2064	99
Researchers in disciplines related to biotechnology (latest available data)	55.578	288.111	8.263
Patents / Researchers (%)	0,71	0,72	1,20
R&D expenditure, million U\$S PPC (average 2010-2018)	5.064	36.126	1.567
Patents / R&D expenditure (%)	7,80	5,71	6,32

Source: Own elaboration based on data from Orbital Intelligence (Questel), RICYT and the Ministry of Science, Technology and Innovations of Brazil

Figure 1. Biotechnology patents applied for with priority. Number per year (2000-2018)



Source: own elaboration based on data from Orbital Intelligence (Questel).

In relation to the relevant actors in the patenting process, there are different profiles among countries. In the case of Brazil, there is a strong concentration of patents among universities and public laboratories, which hold about 80% of the total with low participation by national and foreign companies. In the Argentine case, patenting is led by the National S&T Council, followed by some national companies (Biosidus and Bioceres), Foundations (Leloir Institute), national Universities, and foreign companies. In the Colombian case, patenting is led by public and private universities, foreign multinational

companies (i.e. GSK and Bayer), and other foreign entities. In this case, national companies play a secondary role. These performance indicators show the structural dependence on imports of inputs and drugs, and the low level of patents among national biotechnology companies. Although it is beyond the scope of this paper, some of the reasons given to explain this gap are the scarcity of funding and particularly the absence of venture capital, low private R&D and the tendency of MNC to keep R&D in their headquarters.

Table 5. Summary of comparative performance of innovation systems

Argentina	Brazil	Colombia
Predominance of importing from MNC 42 companies in the area of biotechnology for health. Representing 24% of the biologics market Representing 0.07% of the total number of manufacturing companies. 393 patents applied for with priority (2000-2018) (7.8 per \$ spent on R&D) (Majority CONICET, universities, foundations, and some domestic companies). Others: Biotech companies invest 7 out of every 100 USD of their sales to R&D activities. Local biotech companies are pioneers in the region, since the '80s (pharmaceutical origin and scientific system)	Predominance of importing MNC 96 companies in the area of biotechnology for health. Representing < 10% of the biologics market Representing 0.03% of total manufacturing companies. 2064 patents applied for with priority (2000-2018) 85.7 per \$ spent on R&D) (80% universities and public Labs) Others: High (relative) level of patents by public universities. But... low innovation capacity of local companies (only two entirely Brazilian biopharmaceuticals). Strong vaccine production capacity, concentrated in public laboratories (Fiocruz and Butantan) (94% self-sufficiency).	Control of importing MNC 2 in the area of biotechnology for health. Representing 0.03% of total manufacturing companies. 99 patents applied for with priority (2000-2018) (6.3 per weight spent on R&D) (led by universities and MNCs). Others: Low innovation capacity and lack of local industrial capacities. Biological production is not on the agenda. No significant changes in the status quo are foreseen in the coming years.

Source: own elaboration.

The comparative analysis shows that Argentina and Brazil improved their performance in the biologics segment in recent decades. Both countries have a relatively developed pharmaceutical sector, which has played an important role in serving the domestic market since the '1980s, and took significant steps to redirect efforts towards the biologics segment. In Argentina we observe a greater development of this segment, with a greater presence of private companies, and a more diversified production; in Brazil, the public sector and a group of multinational companies have a greater leadership, and national production and developments have been more concentrated around vaccines. In the case of Colombia, however, we identified an opposing trend, even to dismantle the incipient capacities that were available before the 1990s. In what follows we analyze the different efforts made in each country for the

development of this segment and the trajectories that explain this performance, as well as some key qualitative characteristics that distinguish the systems of each country that should be taken into account with the objective of using their experience to illuminate policy decisions in other countries of the region.

5. Case studies

In this section, we analyze comparatively the performance of the three selected countries, highlighting their distinctive features and performance taking into account the five dimensions highlighted afore: (a) industrial capabilities, (b) S&T capabilities, (c) health capabilities, (d) interministerial coordination and (e) the intensity of the links between actors and their interrelatedness.

4.1. Argentina

Industrial capacities

Argentina presents one of the greatest capacities for R&D and manufacturing of biological products in Latin America. Similar to Brazil, capabilities are mainly focused on the production of biosimilars, through the entry of patent-expired biotech drugs into the market. With the exception of one company, Argentina does not develop products at the frontier of the biologics market. Capacities are supported by a strong national pharmaceutical sector, a relatively developed scientific system, and the emergence of new specialized biotechnology companies. Policies -from patents to industrial policy- tended to favor domestic drug companies in their competition with MNCs. Capacities could be strengthened through institutions that promote inter-ministerial coordination and the intensity of science-production linkages.

Multinational laboratories participate in the biologics market with imported products, while Argentinian companies do so through local production of therapeutics, reagents, and biological vaccines. The first companies established in the area of biotechnology for health emerged gradually since the 1980s. The expiration of patents on first-generation recombinant proteins gave rise to a local production market for biotechnological drugs. The emergence and growth of a biologics production sector in Argentina can be explained in large part by the pharmaceutical sector's ability to take advantage of the emergence of the biosimilars market in this early stage. It is worth noting that a distinctive feature of the Argentine pharmaceutical industry in the Latin American context is the significant participation of national companies, which were favored early on by a series of policies - from intellectual property protection to industrial policy. Early investment in universities, protectionism, and the absence of patents until the end of the 1980s were decisive in the consolidation of local drug production by national companies, which, similar to Brazil, expanded on the basis of copying. Local developments were mainly based on processes of copying molecules/proteins developed and patented abroad, with innovations in production processes, some of which led to the granting of patents

(CEyS/FIDE 2014). Other developments arose as spin-offs from initiatives of pharmaceutical companies, as local startups originating in the STI system, and from state purchases.

In addition to the above companies with development and production capabilities in the biopharmaceutical sector, there are about twenty national firms with R&D capabilities in biotechnology for health. These small-sized companies, most of them created since the 2000s, have multiple origins: productive scaling up of academic theses from biotechnology or related careers, spin-offs from research groups of public institutions that independently or in association with private companies create productive enterprises, and spin-offs from established pharmaceutical or biotechnology companies and initiatives of consolidated companies in related activities that develop independent business units in biotechnology (MINCyT 2016).

On that end, it is hard to affirm that there were explicit coordinated policies towards a national biologicals system, but individual initiatives of pharmaceutical companies attempting to increase their competitiveness and resourcing from regulatory vacuums in the 1980s and 1990s. In a scenario of strict regulatory health policies enforced by ANMAT these also pushed towards softer regulations in terms of IPR that allowed the emergence of domestic capacities. The larger biotech companies promoted since 2011 the creation of a Biotech Chamber to advocate for better policies to protect the sector and also invested in the creation of new startup accelerators that would spill innovative dynamism into the system.

The production of biologics, both in Argentina and Brazil, is leveraged on existing productive capacities in the production of drugs. In both countries, domestic drug production accounts for most of the local market (while the penetration of drug imports is lower than in the Colombian case). The sector shows a good performance in terms of production, exports and innovation. In 2019, sales by domestic companies in the sector accounted for 68.4% of units sold and 67.9% of sales value (CILFA 2020). In recent years, the domestic industry was growing even from the acquisition of industrial plants of international companies in the country. Since 2000, there have been twelve such acquisitions. Of the 229 manufacturing plants in the pharmaceutical industry, 181 are national (80%) and 48 are foreign (20%). Among the first ten pharmaceutical companies, in terms of turnover, the first eight are national, accounting for 47% of the total turnover (CILFA 2020). Domestic laboratories not only supply a large part of the domestic market, but also export to other markets. The export activity of the Argentine pharmaceutical industry makes the country the third largest exporter of pharmaceutical products in Latin America behind Mexico (1,773 million USD) and Brazil (1,183 million USD). Even when well behind in international terms, the pharmaceutical sector is one of the most innovative sectors in the country, accounting for 26.13% of total industrial R&D expenditure. The effort in innovation activities in the sector has

been increasing in recent years - between 2005 and 2018 the increase is estimated at 212% (from USD 64 million to USD 200 million).

Scientific and technological capabilities

The Argentinean scenario shows a strong impact of STI policies (especially, instruments by the National Agency for the Promotion of R&D and Innovation under the Ministry of STI) and, more generally, of the capabilities and trajectory of the local scientific system that promoted topics associated with health (rooted to the early 20th century), molecular biology and biotechnology (since the '1970s and '80s). There are 54 scientific institutions in the country that carry out R&D in biotechnology in human health, a significant number of degree courses in biotechnology and related disciplines, and one of the highest levels in the region in terms of R&D personnel per thousand economically active people, academic publications in biotechnology and biomedical engineers per 10,000 people. Although industrial policy in Argentina has a more unstable and discontinuous trajectory than in Brazil, since the '2000s it has been strengthened and has many instruments for intervention. Similarly, Argentina has strong regulatory frameworks for the approval of drugs and biological products.

Table 6. STI capabilities

STI capabilities	Argentina	Brasil	Colombia
Spending on science and technology activities	0,5	1,5	0,69
Spending on R&D	0,49 PBI	1,26	0,27
Amount of researchers	87.898	421.838	13.001
R&D personnel per thousand EAP	4,8	3,3	0,5
Publications (Number of articles registered in SCOPUS, 2016)	13.904	74.717	10.411

Source: own elaboration

Health capacities

These present a lower weight in the innovation system than in Brazil. Although the level of health spending is relatively high and there is a significant development of public drug procurement policies and national vaccination programs, the impact is negatively affected by the fragmentation of the health system⁵. Public procurement programs developed by the Ministry of Health influenced the recent development of the biopharmaceutical sector, and stand out among several health policy initiatives of the last two decades (Vasquez Serrano, 2018). After the socioeconomic crisis of 2001, the national government took several measures to address the problem of access to medicines, including (a) a new national regulatory framework that determines the prescription of drugs by their generic name (Law 25,649); (b) the implementation of the Remediador Plan, which guarantees the free distribution of basic drugs in public

primary health care centers throughout Argentina; and (c) the establishment of a centralized purchasing mechanism to reduce purchasing prices for drug procurement by the Ministry of Health. The importance of government procurement in the health sector originated in the national vaccination programs, which gained great momentum in 2010 and were added to the public purchase of oncological and antiretroviral drugs, and the free provision in public hospitals of drugs to cancer patients without health coverage, channeled through the National Bank of Oncological Drugs (Lavarello and Sarabia, 2015). Between 2007-2015, a series of measures and regulations aimed at promoting the public production of medicines with mixed results, including the creation in 2008 of the National Program for Public Drug Manufacturing (PDM) (later disbanded in 2009), the increasing participation of PDM as providers of the Remediar Plan, the authorization by the national health surveillance authority (ANMAT) that orphan drugs be produced and distributed from public laboratories.

Institutional fragmentation represents an obstacle to promote the industrial sector. The health system in Argentina is composed of three subsectors: (a) public, (b) social security, and (c) private. First, The public sector, through the National State, establishes the health programs for local implementation with public funding. Since public healthcare is decentralized, the provinces are responsible for their public health system (hospitals and care centers), with unequal levels of quality in their attention and facilities. Public services have the entire population as potential beneficiaries, regardless of their ability to pay or their medical coverage. It is estimated that 36% of the population does not access to health coverage via social security or the private sector and resources to the general public system. Second, we find social security is organized on the basis of the social welfare model and mostly channeled by unions. These may be national, provincial or sectorial social health security organizations, which provide protection to formal workers and their families, mostly funded through compulsory contributions through salaries. Also, the National Social Services for Retirees and Pensioners is financed with contributions of active workers and workers. Thirdly, private medicine is organized in around 300 prepaid medicine companies. As contributions to (a) and (b) are compulsory for all tax payers (a) and registered workers (b), it is quite common that the same person pays for their insurance 2 or 3 times (in case they resource to c). This also shows the overlapping and fragmentation on the system, also its inequalities even in a case of universal health coverage.

Inter-sectoral coordination

The country does not possess any entity that addresses the relative dissociation between STI, industry and health policies. Although Argentina has adopted a Sectoral Funds STI policy -inspired by Brazil's model-, they focus on specific projects rather than on capacity building at the sectoral level, have a relatively lower level of resources and tripartite coordination between business,

government and the STI sector is more in the design than in the implementation. Diverse attempts to conform an STI Cabinet for intersectoral coordination or STI initiatives within the Ministry of Health did not thrive. Governance of the STI policy subsystem, historically lead by scientists with low to medium-low connection with industry, and industrial policy, lead by industrial economists with scarce STI background has hindered these connections. Finally, the fragmentation of the health system (public, social security and private), further complicates the possibility of coordinating health policies with STI and industrial policies.

Linkages

The Science-Industry linkage has been historically weak. While R&D agendas are fundamentally nourished by the scientists' interests and capabilities, local industrial needs still have limited influence in their setting. With strong exceptions that now constitute "islands" of Science-Industry cooperation, companies are often unaware of R&D activities and capacities. In addition, patents applied for by residents in Argentina have notoriously decreased between 2005 and 2017. Among residents, applications from public research organizations and universities predominate (55%) while companies account for 30% of applications (MINCyT 2014). This depicts a trajectory of innovation policies with an academicist bias, with a strong "science push" support that exceeds innovation and technology development. As was mentioned, some current exceptions show more favorable links to the development of biologics. An example of these trajectories is that of Mabxience and Sinergium Biotech, both now companies of the Insud Group specialized in the manufacture of biopharmaceuticals and vaccines (respectively). Also, the current emergence of biotechnology based startups that is gaining momentum -mostly, university spinoffs or endeavours based on promising laboratory results enhanced by company builders- also outlines a changing pattern on this end.

4.2. Brazil

Industrial capacities

The country's R&D, Innovation and Manufacturing system for biological products is characterized by the predominance of MNC, incipient development by local companies and strong state capacities to balance innovation and health objectives. Local capabilities are found in the production of biosimilars but especially in vaccines. This result has been achieved with the support of a diversity of policies in the areas of health, science and industry and an institutional framework that favors coordination between the different actors and regulations of the STI system. This complex framework was aimed to balance the objectives of technological innovation and access to medicines. In comparison with developed countries, however, a high rate of technological dependence prevails.

In Brazil, 60 out of 96 biotechnology companies are applied to health. Similar to Argentina, these companies moved towards creative imitator trajectories with emphasis on production (from imported inputs) and developing innovative capabilities. The regulatory framework accompanied these processes and from 2010 specific (abbreviated) pathways were considered to approve biosimilar drugs, with guidelines for different types of molecules, in order to facilitate the development of the local industry (Gutman and Lavarello, 2017). There is a clear market division: the production of recombinant proteins and drugs remains in the hands of the private sector, with a strong weight of MNC importing the finished product or active pharmaceutical ingredients (API), while vaccine manufacturing remains 94% within the public sector. In particular, building capabilities for biosimilar manufacturing became a strong policy target for STI policies in Health, given the increasing pressures the acquisition of biopharmaceutical drugs imposes to Brazil's Unified Health System (UHS).

Brazil stands out for the productive capacity and trajectory of its pharmaceutical sector. It has 241 pharmaceutical laboratories, 144 multinational and 97 national. Most of these companies are oriented to a domestic market of approximately US\$ 10 billion per year, one of the top ten in the pharmaceutical sector worldwide. An important point to note is that, as in Argentina, the Brazilian pharmaceutical industry was able to develop initially thanks to flexible intellectual property systems that facilitated the development of duplicative copycat trajectories, prior to the adoption of TRIPS in 1996.

Scientific and technological capabilities

Brazil allocates a significant amount of resources to research and development, with R&D expenditure of 1.26% of GDP, which is double the regional average of 0.63%. In terms of researchers, it has 3.3 R&D researchers per thousand economically active persons (EAP), well above the 2.1 in the region, although well below the 4.8 in Argentina. In addition to productive and S&T capabilities, the development of institutional capabilities is fundamental, especially those that promote the coordination of policies and regulations at the inter-ministerial level. In this sense, the organizational capacity to coordinate between different areas makes the Brazilian health STI system stand out from others in the region. Among the public policy instruments devised in recent years in Brazil, there has been significant encouragement for coordination between three spheres of the federal government: national health policy, STI policy and Productive Development policy. It was fundamental not only that STI policy was brought closer to health policy, but also that the health sector promoted the incorporation of STI as a strategic axis of its health access policies.

Health capacities

The Ministry of Health plays a leading role in strengthening the production of biologics, using the centralized purchasing power of the Unified Health System (UHS). Since 1990, this provides coverage to 75% of Brazil's population (over 150 million people, making it one of the largest public health systems in the world) and leads a complex institutional framework in coordination with the industrial sector and -to a lesser extent- STI agencies. Brazil's relevance as a pharmaceutical market is remarkable, ranking 8th worldwide. The continental dimension of the country, the universal assurance of the right to health and medicines as essential goods is both a challenge for the public sector and a great opportunity for the development and productive sector.

The “Health Economic-Industrial Complex” (HEIC) (Gadelha, 2003) appeared since 2003 as the main normative framework - developed from academic environments of health economics and sanitation - that guided and coordinated the policy, marking: (a) the articulations between accessibility and economic-industrial policy and (b) the relevance of the health sector as a driver of economic-productive development. This framework focused the policies on two axes: the centralized purchasing capacity of the UHS and the strengthening of the STI system to build capacities to supply the sector. Thus, public health policy was one of the main drivers for strengthening the productive and, to a lesser extent, innovative capacities of the pharmaceutical sector.

Inter-sectoral coordination

Compared to other cases, Brazil has excelled in the development of inter-ministerial coordination mechanisms. Under the conceptual framework of the HEIC, health advisors within the Workers Party, promoted the creation of an S&T institutional framework integrated to the structure of the Ministry of Health⁶. This led also to the creation of diverse policy instruments. A first example of this coordination is the Sectoral Funds policy that created the Health Research Incentive Program (CT-Health) in 2002⁷, which positioned health as a strategic area of national STI production. The mechanism used non-reimbursable funding for the development of STI activities with emphasis on promoting participation and interaction with companies, hospitals, clinics and laboratories. This instated the need for the Ministry of Health to provide the Fund's board a report with the annual priorities of the health system, serving as a map for resource allocation. In turn, during the '2000s, the Ministry of Health implemented several cross-cutting policies meeting the demands of the different g Ministry of Health's Secretariat of Science, Technology and Strategic Inputs (SCTIE/MS), in 2009 the HEIC Executive Group (GECIS) was created, becoming the main coordinating body among these actors, and in 2012 the HEIC Development Program (PROCIS) to strengthen the manufacturing and innovation infrastructure in the public sector, revitalizing public-private

partnerships and encouraging technology transfer in strategic areas for the UHS.

The main instrument for capacity building in biological products were the Productive Development Partnerships (PDP). This were promoted by the Ministry of Health and financed by the Development Bank (BNDES) and the Innovation agency (FINEP), showing the articulation between industrial, STI and health policy actors. Within this policy instrument, some of the main national pharmaceutical companies -specialized in generics- started transitioning towards creative imitator trajectories in biosimilars based on technology transfers by MNC and in association with public laboratories. This transition is taking place in a context in which these companies foresee progressively lower returns from generics, leading those better positioned to invest in the development of biologics, with higher market prices and the possibility of generating higher margins. To date, PDPs yielded moderate results in terms of production of biosimilars for the UHS: many PDPs did not thrive, those that were able to advance further are still in the pre-commercial phase. So far there are only two entirely Brazilian biopharmaceuticals. As noted above, results are much more encouraging in the area of vaccines, in which Brazil has great expertise through its main public laboratories and a strong trajectory of technology catch up through technology transfer agreements (which has lead to developing their own COVID-19 vaccine).

Some praise the PDPs as a tool for reducing drug prices, as a milestone in the country's biotechnology trajectory, which made it possible to create technological and innovation capabilities, train human resources and build synergies between the health, STI and industrial sectors without precedent in Latin America. Criticisms include arguments about the lack of capacity (technical, human, administrative, regulatory) to absorb the program; arguments about transparency and efficiency in the mechanisms for allocating funds and public procurement; the vulnerability of the program to governmental changes; as well as problems in the conceptualization of the program based on the dynamics of the sector and how biotechnological knowledge is produced.

One criticism of the entire policy design is its focus on manufacturing. It is argued that the governance of STI Health policies by powerful actors from the health and industrial sector, aimed at promoting a "nationalization of biotechnology", was based on the internalization of manufacturing capacities based on technology transfer led to a dependent path, as it is dissociated from building endogenous STI capabilities that would allow for to enter a path of long-term autonomy in biologics.

Linkages

Finally, performance is linked to the capacity to create more intense linkages between the different segments of the SSI, particularly between the development of scientific knowledge and productive needs, by promoting public-private articulations or between local and multinational companies and the State.

The institutional framework of the Brazilian health STI system has tended to strengthen some aspects of public-private articulation. In particular, the PDPs aimed to improve the efficiency of the UHS, resourcing to its purchasing power to dynamize capacity building prioritizing HEIC actors. It also sought to improve manufacturing capacity through technology transfer contracts for Brazilian public and private laboratories to produce biosimilars (off-patent biopharmaceuticals), supplying the UHS and controlling the prices of high-cost biological drugs (mainly monoclonal antibodies and vaccines) (Gonçalves and Dutilh Novaes, 2018). An example of this in terms of concrete results is the development of vaccines for the National Vaccination Program, entirely by public institutions (Bio-Manguinhos-Fiocruz, Ataulpho de Paiva Foundation, Butantan Institute and the Ezequiel Dias Foundation) with transfer of frontier technologies by MNC such as GSK, Merck and Sanofi Pasteur (Gadelha et al, 2019). Likewise, the negotiation capacity of the Brazilian state with MNC constitutes an emblematic case also in the use of compulsory licenses (LC) to negotiate prices with multinational pharmaceutical companies, allowing improved access to patented drugs, particularly in the case of antiretrovirals (Urias, 2019). Meanwhile, even when 95% of Brazilian biotechnology companies declared to maintain active interactions - 70% formal relationships- with universities and research centers (Alves et al, 2017), these have not translated concretely into innovations in health.

4.3. Colombia

Industrial capacities

Colombia's system stands out for the high presence of MNC and import penetration. The objectives of attracting investment through a strict patent system and the signing of free trade agreements played an important role in delineating the country's industrial features. Compared to Argentina and Brazil, it has less scientific and industrial capacities and weaker policies in these areas. There are also no initiatives to align the actors participating in the innovation system. These features explain the greater technological dependence, lower rate of invention and lower capacity to produce biological products.

The Colombian pharmaceutical sector differs from those analyzed here by the greater relative presence of MNC. Considering 2012-2017 sales, only one national company integrated the top-10 list. An important precedent dates to

1957, with the installation in the local market of 70 foreign laboratories after signing an agreement with the government that guaranteed protection to their products through patents. This has implications on the profile of the industry's interests and the policies it promotes. In the '2000s, as a result of a process of acquisitions of national laboratories by foreign groups, there tended to be a greater convergence of support for certain measures, including the strengthening of patents and the signing of free trade agreements (Conde Gutiérrez 2020). The sectorial profile has a breaking point in the 1990s, in the trade liberalization strategy carried out by Colombia which not only involved a tariff reduction for the entry of pharmaceutical products, but also the adoption of even stricter standards than those committed to under the WTO agreement on TRIPS (TRIPS+).

This results in higher level of imports: in 2016, the proportion of imported drugs to the total domestic market was 64%, compared to Argentina's 39% and Brazil's 36%. Recent developments were characterized by a fall in the number of production plants and an increasing weight of imported drugs in the local market, causing an increased trade deficit. According to ASINFAR (2018), this has been the result of the lack of a productive policy for the sector. As a result, we see a division of labor in the pharmaceutical market: while domestic laboratories specialize in the most prevalent market segments, MNC specialize in specialized drugs, including biopharmaceuticals (ASINFAR 2018). This leads to imported drugs to account for 82% of the institutional market in terms of amounts but only 17% in terms of therapeutic doses, while domestically produced drugs account for 18% in terms of amounts and 83% in terms of doses. About 47% of the institutional market corresponds to specialized therapies, with a high participation of biological drugs, which account for 25% of this market, approximately (ASINFAR 2018). MNC make no R&D investments in the country and none of the top 50 global companies have plants in Colombia (Fitch Solutions 2020). In Colombia, biopharmaceutical start-ups are still incipient, also related to a less developed biomedical S&T tradition.

Scientific and technological capabilities

Public and private spending on S&T activities ranks below the regional average with 0.69% of GDP⁸. When considering, in particular, spending on R&D activities, Colombia's relative position falls even further (0.27%, while the average for the region is 0.66%). In particular, health biotechnology projects funded by the Ministry of Science averages 4% of the total projects, showing a less developed biomedical tradition than the previous countries. A distinctive feature of Colombia is that the private sector accounts for over 48% of general S&T expenditure, thus orienting R&D agendas. Between 2013-2019, the amount of health biotechnology research groups expanded from 6 to 37. In addition to having grown the number of higher education institutions from 5 to 17, actors from other sectors were incorporated.

Health capabilities

Despite having an above the regional average health expenditure and a high level of coverage⁹, the health system does impact positively on domestic capabilities. Health policies remain oriented to guarantee access and attract investment rather than to promote local manufacturing. The National Health Institute (NHI), agency that depends from the Ministry of Health, remains as the national public health reference and coordinator of epidemiological surveillance networks, laboratories, organ and tissue donation and transplants, blood banks and transfusion services. However, in terms of R&D and manufacturing, its capabilities -similar to Brazil and Argentina before the 1990s, were restricted to the production of antiophidic sera (Daguer, 2018).

Despite meeting the requirement of broad coverage, numerous problems have been identified in the health system, among which are the inequitable distribution of resources between regions of the country, the exclusion of services that are in high demand from the Obligatory Health Plan (POS), differences between the services offered in the contributory and subsidized regimes (Suárez-Rozo et al. 2017). More than half of the pharmaceutical market is explained by purchases made through institutional channels, i.e., transactions with health system entities that are paid with public funds. The drug pricing policy, the competence of the National Commission on Drug and Medical Device Pricing, is also criticized for punishing domestic manufacturing companies. Law No. 1753 (2015), which establishes the National Development Plan 2014-2018, puts into operation the new system of centralized negotiation of medicines, inputs and devices. This law empowered the national government to intervene in the market with the purpose of guaranteeing access to medicines by the population. Although it recognizes that the system has generated significant savings for the public budget, ASINFAR points out that the system has a negative impact on local manufacturers (which correspond to the bulk of its affiliates), since it is applied indistinctly on institutional and commercial sales. In turn, it notes that the government's willingness to apply mandatory licensing conditions for medicines enabled by legislation for public health reasons or for generic production has been very limited (ASINFAR 2018).

Regulatory standards go in the same direction. Framed in its foreign policy aligned to the United States and OECD and with the aim to attract foreign investment and endorsement amidst the fight against guerrillas, since the 1990s Colombia has incorporated strict health regulation standards (additionally to enforced IPR ones). The food and drug surveillance agency (INVIMA) has been recognized as a regional reference authority, by adhering to internationally harmonized criteria (Good Manufacturing Practices, Good Clinical Practices, International Committee for Harmonization standards). The accelerated adoption of these standards created further asymmetries between MNC and domestic companies: while imports for products approved by FDA and EMA

were simplified, the approval of local facilities and products were slowed down. These led to a process of local deindustrialization, the closure of local plants and even the transfer MNC manufacturing to other countries since the 1990s. The adoption and strict enforcement of GMP standards, dissociated from a policy of industrial adaptation (such as the one implemented in Brazil), had a strong impact on the local productive structure and led to the closure of the industrial fabric of private laboratories that could not adapt to the new sanitary standards. The same happened with the public production of biologics (serums and vaccines) of the National Institute of Health, whose productive capacities were largely dismantled.

Clinical trials remains as the one area that could be singled out as an exception in terms of increased health regulatory capabilities, as the government facilitated the incentives for MNCs to carry out their rituals in Colombia (for instance, reduced times for approval¹⁰). Here also the regulation favors MNCs over domestic production.

Inter-sectoral coordination

In Colombia, institutional weaknesses are found both in the level of coordination and in regulatory capacities. Industry stakeholders consider that the National Institute for Drug and Food Surveillance (INVIMA) suffers from problems that affect the competitiveness of the sector. Among them, the slowness in the evaluation and granting of sanitary registrations, the congestion for the certification visit of production plants, the slowness in the approval of research protocols for certain types of scientific studies stand out. According to the diagnosis prepared by ASINFAR (2018), the deficiencies in the training area also extend to the officials of regulatory bodies. In particular, this situation is more acute in issues related to the regulation of new technologies and technological innovation.

Linkages

In Colombia, despite national discourses, the scarce of funding to S&T also entails weak linkages between the SSI actors (Colombia Productiva 2019), without any incentives to promoting sectoral development. Academic actors prioritize publishing agendas, disregarding application purposes. The weakness of the pharmaceutical productive sector and the absence of an industrial sectorial plan does not contribute to strengthening the biologics SSI. This deepens even more capacity building strategies and bridging from laboratory experimentation to industrial scales. As was mentioned, capacities in clinical trials can be singled out as a growing sector.

5. Discussion

Table 7 systematizes the main features described above in selected dimensions to conduct a cross-case comparison of the profiles of the SSI in biologics. The

assessment made in the different dimensions are expressed in relative terms (high/medium/low, strong/weak) to the rest of the Latin American countries considered in the study. The performance of the countries is influenced by the five dimensions we outlined as critical for the SSI in biologics (industrial, S&T and health capacities, as well as the intersectoral coordination and density of the linkages between actors). As posited in Section 2, considering regulatory making both a key determinant that shapes innovation pathways (ex post but also ex ante) while, at the same time, a byproduct of power negotiations, we included this dimension unfolded into the two main regulatory tracks that deemed relevant for the study, the international trends to enforce the adoption of health surveillance standards (such as GMP and GCP promoted by the WHO) and IPR rights through TRIPs, both during the 1990s.

Table 7. Comparison of the profiles of the sectoral health R&D and innovation systems

Country	Argentina	Brazil	Colombia
Health capacities	Medium Fragmentation: public system, social security, prepaid medicine	High UHS 75% population Health access policies / medicines National vaccination program	Medium Health spending above Latin American average Fragmentation
Industrial capacities	Medium/High Diversified in products, with presence of domestic companies*. + Domestic companies (70% of the pharmaceutical market) + Protagonism in biologics Important R&D policy, + local pharma sector lobbying	Medium/High Concentrated, with dominance of EMs*. + Domestic companies 65% of the market + organic segment dominated by MNC Autonomy in vaccines (94% of market by public laboratories) Important production policy initiated in 2003, plus lobbying by MNCs.	Low Lower value synthetic products Pharma industrial facilities closed in the 1990s Domestic production represents 18% of the market
STI capacities (R&D investment and scientific capabilities in health, molecular biology, biotech)	High diversified Strong STI policy and historical trajectory 54 Scientific institutions R&D in biotechnology applied to healthcare	High in biosciences Medium/low in biotechnology applied to healthcare	Low Medium in health and clinical trials
Inter-ministerial coordination (STI-Industry-Health)	Low Ad-hoc coordination (e.g. during pandemic)	Medium/high Various programs and institutions (2003-2016), leadership of Min Health (to ensure access).	Low
Stakeholder linkages	Strong: Biologics "network companies" (R&D agreements with MNCs, scientific institutions) But weak nexus between pharma sector -STI-production system	Strong between health and industry (HEIC) Weak between S&T based companies , academic imprint of the STI system.	Weak
Regulation: Intellectual Property Rights	Weak Key in the development of productive capacities	Pre 1996: Weak Post 1996: Strict but with compulsive licenses	Strict+ (TRIPS+) Pattern of international insertion and adoption of international standards
Regulation: health surveillance	Strong (regional reference) Adherence to international standards for domestic companies to meet global markets	Strong (regional reference) Adherence to international standards. Process of adaption with industrial capacities	Strong (regional reference) Adherence to international standards without adaption led to desindustrialization

Source: own elaboration

At the risk of simplifying, this scheme allowed to identify three paths in these three countries that highlight general attributes in a comparative manner. In all cases, policies discursively promoted the importance of innovation to strengthen healthcare capacities but each showed a different path for it. This reflects each country's historical trajectory, international insertion, and domestic power balances, leading to diverse forms of setting the directionality of the SSI in biologics as a result of negotiations between conflicting choices and cultural values.

Schematically, we may characterize Argentina as a “fragmented industrial sovereignty” type. This reinforces an historical quest for (bio)technological autonomy coated with a nationalist discourse that coexists with a weak linkage between academy and industry, a political academicist STI culture (dominated by the scientific community) and a political culture of sectorial silos. Despite this, the country's IPR scheme allowed for a sound capacity building process in the area with a larger participation of domestic pharmaceutical companies innovating in biologics with more relative power and influence on domestic policies (and its enforcement of IPR). Here, the Argentinean SSI has as its main goal and direction to support national manufacturing biopharmaceutical firms. Even when it has not promoted a coordinated strategy for that end, these firms have been benefited by public subventions for innovation as well as specific public purchasing agreements as well as the state not pursuing stricter IP standards.

The case of Brazil can be framed as one of “coordinated neo-industrialism”, attempting to substitute imports through technology transfer agreements as a mean to catch up. The diverse policies that brought together the Health, STI and Industry policy subsystems -even with its flaws- appears to be a distinctive feature within the Latin American scenario. This case is characterized by a vast array of institutions and laws that since the 1990s aimed to balance between: (a) the need to attract foreign investment (therefore, seeking to benefit MNCs); (b) guarantee access to health within one the largest health system coverages, which sees universal health coverage as a constitutional right and drugs and vaccines as social goods, in front of the growing budgetary menace posed by high priced biotherapeutics, which requires substituting imports; and (c) promote a highly developed pharmaceutical industry -and its corporate group- which faced a progressive loss of competitiveness and market share in front of the advancement of the biopharma, also in a country where MNCs retain political power. In Brazil, while strengthening IPR in the 1990s was detrimental to the local generic drug companies, the adoption of enhanced health regulatory standards was accompanied by national policies that helped domestic labs to adapt to the new scenario.

The Colombian case, which we would label as “deindustrializing liberalism”, became one of the triggering motives behind this paper, showing behind the “innovation imperative” discoursiveness (Pfotenhauer REF) a contrary trend:

instead of moving towards capacity building for more autonomous health systems, the conflicting policy choices for this sector were in fact affected by the country's foreign and internal security policy. From that end, health system's resilience was overthrown by the more critical goals of attracting foreign investment and retaining USA's support for internal policy on security affairs, facing the guerrillas and drug trafficking.

6. Conclusions

This paper aimed to understand the working and delivery capacity of SSI in biologics in three middle income Latin American countries, understanding how these systems were shaped, which elements determined their trajectories and orientations, also understanding innovation in the health sector interrelated with other policy subsystems. We attempted to depart from an "innovation as imperative" discourse that would entail capacity building towards competitiveness as desired feature of the system, to understand the sectorial configuration as a conflicting process that results from negotiations between diverse power coalitions (between diverse government actors, national and foreign actors, from the scientific community, MNCs, national pharma industry, startups, unions, health actors, regulatory agencies, public opinion, among many others). Both implicit and explicit policies depicted each countries coalition forces, preserving or attempting to transform the status quo and stirring the wheel towards distinctive directionalities. Here, each SSI and its results in terms of delivery remain shaped by the specific characteristics each national political economy (institutions, economic structure and interests), the objectives and issues prioritized by the diverse governments, and the political space provided (or not) by the international context and rules

This aims to open the reflection on the ultimate systemic aims and what they actually aim to the deliver (is it access to health, promoting competitive domestic firms -and which firms-, attracting more foreign investment, assuring security policies...?). This approach aimed to include a political economy uptake of the SSI, setting aside an understanding of innovation as the primary end -and therefore a one way approach towards capacity building-, but showing the multiple pathways innovation may adopt, based on the political commitments, cultural values and political aims, which not always refer to the health sector itself. On that end, the Colombian case serves as an interesting learning input that innovation systems may have multiple aims, innovation being an mean towards further policy aims. This also serves as a learning from historical innovation policy imitative trends, with an endless transferring of institutional models and instruments that bypass their original socio-technical arrangements and political commitments on what was relevant to deliver.

As the cases showed, there is not a more or less efficient or inefficient system but an orientation towards each State policy aims understood as "public good" or visions of desirable futures, stabilized as we discussed by the dominant

coalition with the power to impose this sense-making, which rely on broader national (cultural, ideological, political) agreements that become coproduced with the system itself. Different systems are more or less effective in meeting different objectives, which often come into tension. The paper also shows how each country's adhering to diverse regulatory frameworks under these diverse understandings of "public good" shaped their innovative pathway. It goes without saying that this implies that any policy recommendations are not neutral and will favor some goals and actors over others. Building more resilient and accessible SSI in health has served as a legitimacy promise to deploy innovation policies in health, but has not served necessarily as a concrete directionality aim. Following Alice's Cheshire Cat through the rabbit hole of innovation, requires fitting means to ends, since where to go depends in a great manner on where we want to get to.

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Notes

- ¹ Number of local biotechnology companies applied to health, sales volume, market share and dependence on imports, etc.
- ² Patents applied for by residents and add an analysis of those that were applied for with priority to approximate the participation of developments carried out locally.
- ³ Foreign laboratories import up to 96% of the biotechnology products they offer in the domestic market, accounting for most of the trade deficit related to these products (Gutman and Lavarello 2017).
- ⁴ These figures can be seen as part of a worldwide trend in which demand for biologics is growing at higher rates than traditional medicines (Gutman, 2015).
- ⁵ Argentina's spending on health was 7% of Gross Domestic Product (GDP) in 2017. These values place Argentina above the average of Latin American and Caribbean countries (4%) and the world average (6%), and at a value very close to the average of OECD countries (8%). The State is the main financier of health, accounting for 72% of total spending. State efforts in health policy are proportionally high when compared to the state financing of health spending in the OECD (61%) and in Latin America and the Caribbean (52%). Following a global trend, in Argentina public expenditure for health increased from 55% in 2000 to 72% in 2017.
- ⁶ The link between the needs of the health system and the STI sector had its first institutional antecedent in the First Conference on Science, Technology and Innovation in Health (CTI-S) in 1994, which recognized the importance of the double social and economic dimension of this articulation (instead of the traditional conception of social as something subsidiary to economic competitiveness) (Tomassini, 2016).
- ⁷ Since its creation in 2002 until 2014, the CT-Health fund financed more than 1400 projects for a total value of more than R\$ 200 billion, and CT-Biotec financed 630 projects for approximately R\$ 120 billion (MCTI 2016, in Tomassini, 2016).
- ⁸ The LAC average is 0.94%. However, since 2008, its growth has been well above that of the rest of the region, both in relative terms to GDP (+30.1% vs. 8%) and in absolute terms (95.7% vs. 44.6%).
- ⁹ The health system has broad but fragmented and unequal coverage. The profound reform of the health and social security system in 1993 succeeded, through a system of a public-private nature, in bringing the level of access to health from 23.7% to 96.9% in 2020 (Ministry of Health and Social Protection, 2020). The system is financed by contributions from salaried workers, self-employed workers with contributory capacity and pensioners, and by contributions from the State. Approximately, the contributions of 50% of the population cover 70% of the system's expenses, while the remaining 30% is assumed by the State (Mendieta González and Jaramillo 2019).
- ¹⁰ The country had very long delays in approval times by the regulatory body (an average of 165 days) and the ethics committee (50-60 days). In total, the process took 225 days. In Singapore, the leading country in this field, approval times are 30 days. But even Argentina and Brazil, countries that also have relatively slow approval processes, were below Colombia with 180 days on average (Pugatch Consilium 2016).

Novel frameworks for inclusive innovations: Lessons from MedTech innovations for cancer in India

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Abstract

Cancer detection in low-resource healthcare settings remains a significant challenge, with early detection modalities like mammography and pap smear tests predominantly rooted in industrialised nations. In recent years, the Indian MedTech sector has witnessed a surge in artificial intelligence (AI) and machine learning (ML)-driven innovations. This paper explores three case studies of point-of-care MedTech innovations for breast, cervical, and oral cancer developed by Indian Medtech startups. These cases address unmet needs and challenges associated with early cancer detection in resource-constrained environments. The paper introduces the Inclusive Health Innovation (IHI) framework, developed by integrating and extending the sectoral system of innovation approach (Malerba & Mani, 2009) and the institutional triad of healthcare (Srinivas, 2012). Using the IHI framework, this paper (i) elucidates inclusiveness in MedTech innovation, encompassing both process and outcomes of innovation, and (ii) identifies institutional bundles fostering inclusiveness. The paper concludes by offering public policy insights through inclusive innovation for early cancer detection in low-resource healthcare settings.

Keywords: Inclusive innovations; Unmet needs; Cancer; industrial innovation systems; MedTech; health care delivery, industrial policy; health policy; low- and middle-income countries; India.

JEL: B15, D02, E61, I14, I18, L52, O2, O3

1. Introduction

This paper conceptualises inclusive innovations by studying innovation process and outcomes of the emerging medical technologies (MedTech) innovations for the early detection of cancer in India. To do so, this paper has twofold objectives. First, to propose a novel approach, Inclusive Health Innovation (IHI) framework, to study the technical change in the MedTech sector in India with a lens of inclusiveness. IHI framework does so by facilitating a deeper understanding of innovation process of emerging innovations within the broader political economy of Indian health care system. Second, to highlight implications for public policy to channel development and adoption of such inclusive innovations in the health delivery systems such that industrial capabilities can be oriented to address complex health challenges.

MedTech innovation combines research, technology, and clinical practice, to facilitate timely detection, diagnosis, and treatment of complex health challenges. To create a broader impact, scholars linking innovation and development suggest that innovations must be inclusive and responsive to the needs and interests of the population. This paper focuses on India because it presents a challenging and paradoxical landscape in which a strong healthcare industry co-exists with a large section of the population bearing a triple burden of diseases and inadequate access to affordable healthcare. In terms of cancer, in a population of over 1.3 billion people, India has the second highest mortality due to cancer (851,678) and the third highest estimated new cancer cases (1.32 million) in the world (IARC, 2022). Breast, cervical and oral cancers constitute the leading causes of incidence and mortality in India (GBD, 2019) (see Appendix A1 - A4). Literature suggests that timely availability and access to affordable early detection, i.e., screening, and early diagnosis, modalities can substantially reduce premature mortalities and the cost of the treatment (IARC, 2020). However, the gold standard early detection modalities for breast, oral and cervical cancers in India, including mammography, pap smear tests, HPV DNA test, etc., are not conducive to low-resource healthcare settings. These are primarily designed for use in high-income countries, largely unaffordable to a large section of the population, and not conducive for low-resource healthcare settings. Studies suggest that even when modalities are cost-effective, they may not be efficient in low-resource healthcare settings due to factors other than affordability. For example, clinical breast examinations are a widely accepted low-cost modality for screening in Indian settings. However, the effectiveness of successful screening depends upon the expertise of the clinician and healthcare workers (Mehrotra & Yadav, 2022). As a result, there are huge concerns over the lack of availability and access to affordable and appropriate Medtech for cancer detection. Comprehensive studies have captured the public health implications of a mismatch between health and unmet clinical needs and medical device and diagnostics research (Mahal & Karan, 2009; WHO, 2010;

Chaturvedi et al., 2015). The mismatch between available medical devices and the needs of the health sector includes two key aspects (WHO, 2010). First, the existing supply of medical devices includes those acquired irrationally without sufficiently assessing for specific health outcomes. Second is the absence of an effective counterforce to absorb the large numbers of medical devices coming to the market. As a result, the solutions offered by existing innovations have not been appropriate to the specific local conditions. Kale and Wield (2019) attribute this mismatch to a lack of 'collaborative action' at various levels in the medical device sector. They elaborate 'collaborative actions' as 'reflective public policy activities to support capability development between myriads of different public and private institutions and organisations along with a wide public to private spectrum' (ibid).

Given these challenges, several scholars emphasise the importance of locally available and affordable innovations to balance the global agenda of improving cancer outcomes. Reflecting upon an analogy describing the range of innovations available for cancer, the following quote from Sullivan, Pramesh, and Booth (2017, p328) states:

'Cancer 'moonshots' may improve individual outcomes in high-income countries with strong governance, but they will not solve the rising economic and social burden of cancer globally. What we need are 'earthshots' that focus on building infrastructure and delivering affordable, equitable and effective care.'

In recent years, the Indian MedTech sector has witnessed a surge in point of care (PoC) innovations driven by artificial intelligence (AI) and machine learning (ML) for the early detection of cancer that show some signs of inclusiveness. These context-specific innovations are developed by MedTech startups that aim to address unmet needs and challenges of the early detection of cancers in the Indian context. These emerging MedTech innovations in India offer a crucial opportunity to (a) study the institutional bundles that have led to this change in the larger medical device sector in India (b) investigate the massively underemphasised relationship between STI, industrial and health policy.

This paper has five sections. Section 2 provides the conceptual basis of understanding inclusive innovations and critically reviews existing frameworks and proposes IHI framework. Section 3 elaborates on the research methodology to illustrate the framework's applicability for emerging MedTech innovations in the early detection of cancer in the Indian context. Section 4 provides emerging insights from data collected for the case studies and discussion on inclusiveness. Section 5 concludes the theoretical and empirical observations of this paper and offers public policy considerations.

2. Theoretical underpinnings and conceptual basis to study inclusive health innovations.

This section presents the conceptualisation of inclusiveness in innovations, and health innovations, by reviewing the literature. To begin with, it is crucial to refer to the evolving meaning of innovation to set the discussion of this paper. Innovation is traditionally referred to as (the use of) a new idea or method. Over the years, scholars of innovation studies have proposed a broader view of innovations (for instance, Freeman, 1987; Lundvall 2004). They define innovation as a continuous cumulative process comprising both radical and incremental innovation, and the interactive learning in diffusion, absorption, and use of innovation highlights the major source of innovation is not necessarily science. For instance, WHO defines health innovation as a multidimensional concept – not merely a product/process innovation – which encapsulates the development of 'new or improved health policies, systems, products and technologies, and services and delivery methods to 'improve people's health', with a 'special focus on the needs of vulnerable populations.' Many studies, for instance, Abrol et al. (2016), have highlighted health innovations as a complex interplay among political, administrative, technological, institutional, and legal issues. However, the structure and dynamics of health innovations are often assumed and studied in silos (Consoli and Mina, 2008). As a result, they are defined narrowly as new drugs, devices, and vaccines. Their development process is either studied in isolation from the broader socioeconomic framework of systems or disconnected from the health care delivery system (ibid; Srinivas, 2012). Therefore, a broader understanding of innovation calls for deeper insights into inclusiveness at various levels – at the level of the innovation process and outcomes it impacts.

To understand how 'inclusiveness' is captured in the literature in the context of innovation in general and the health sector in specific, I pose some questions: what inclusive innovations are and for whom? Why are they highlighted in the developmental challenges? Engaging with these questions as I review the literature seems pertinent because the role, meaning, and process of innovations have an instrumental role in the early detection of cancer, mainly due to its complex relationship with inequality and poverty.

2.1. Understanding inclusive innovations

Historically, despite increasing burden of oral, breast and cervical cancer there have been lack of availability of locally relevant technologies. This issue becomes concerning when the health needs of high-income countries drive innovations in the health sector. For instance, for several years, medical devices and diagnostics in India largely involved reassembling imported parts with little value added to make it commensurate to the local environment. This is also captured by a WHO report based on the Priority Medical Device project (WHO, 2010; p2):

‘Medical research priorities in most high-resource countries are based primarily on scientific and technological preferences, with little explicit regard for public health needs. In consequence, information about medical conditions and diseases does not translate into effective management of local health systems, nor does it translate into efforts to build the capability of low-resource countries to conduct and use research and to become technology innovators themselves.’

The resulting inadequate supply of appropriate and poorly working medical devices poses a significant challenge to Indian health systems. First, due to the challenges of integrating imported device and diagnostics into local health systems, particularly at the primary level of care, because of the skill requirements for sophisticated operations (ibid). Second, there are impediments due to low public health spending, ill-defined procurement, varying implementation of regulations, and the absence of health technology assessment. It contributes to widening disparities due to the lack of availability and access to affordable and locally appropriate medical care (WHO, 2012). In the case of cancer, the lack of access to appropriate early detection modalities in India has been raised as a critical public health challenge. For instance, routine mammography screening, which is widely accepted in western countries, is not a favoured option for India's low resource healthcare setting (Mehrotra & Yadav, 2022).

The co-existence of dominant or so-called mainstream innovation and perennial health challenges echoes Richard Nelson's reflection on the USA of 1970s in his work, *The Moon, and the Ghetto* (Nelson, 1977, 2011). He questioned how nations have capacities for missions to the moon amid unaddressed social ghettos. This reflection also connects with the policy debates on cancer moonshots and earthshots. The frameworks for *moonshots*, including defining the problem supporting it with funds and technical expertise to solve it in a given timeframe, is somehow difficult when applied to more complex or wicked problems (Nature 571, 145 (2019)). Scholars, including Mazzucato (2017) recommend that policymakers adopt a participative and inclusive approach to support moonshot-style grand challenges or 'missions'. Mazzucato explains that doing this requires defining problems, implementing solutions and dynamic progress monitoring, as opposed to the market failure framework of static 'before and after' cost-benefit analyses (ibid). Mission modes are tested to be a successful approach in advanced economies as they make innovation efforts goal oriented within well-defined systems of innovations. However, how feasible are they for complex issues like access to early detection technologies for cancer in India? Historically, having 'missions' to resolve Indian healthcare challenges have resulted in the creation of several 'siloes' disease verticals. Also, in under resourced health systems, how can the state do dynamic progress monitoring? What about the local health needs? Next, I attempt to engage with some of these questions, by reviewing how

inclusiveness in innovations has been approached in general and in low-resource settings.

To fathom innovations' inclusiveness, scholars highlight innovation and technological change, resulting from the growing global diffusion of technological capabilities and entrepreneurship in the rapidly rising late industrialising economies (Chataway et al., 2014). Given stark global disparities, the scholars linking innovations and development highlight such innovations as 'inclusive' and a critical ingredient of development (Kaplinsky, 2011). In this sense, the 'narrative of innovation' has a central role within this broader policy discourse wherein innovation is framed as a critical ingredient of development. LMICs are seen as a significant driver of global innovation in the 21st century (Kaplinsky, 2011). Particularly by way of their contribution to growth, use of factors of production, the social relations associated with production, and mainly the characteristics of the products they produce (ibid). Such innovations that aim to foster the development and implementation of new ideas, aspiring creation of opportunities that enhance the socio-economic well-being of all, particularly for the poor and marginalised section of society, have been broadly termed as 'inclusive'. In innovation and development literature, scholars have highlighted such emerging inclusive innovations with a range of terminologies, including 'jugad innovation' ', frugal innovation', 'BoP (bottom-of-the-pyramid) innovation', 'below-the-radar innovation', 'scarcity induced innovations', 'social technologies' (Prahalad, 2005; Srinivas & Sutz, 2008; Chataway et al., 2007; Altenburg, 2009; Foster & Heeks, 2013; Kale et al., 2013; Chataway et al., 2014; Gras et al., 2019). This paper builds on the ladder of inclusiveness by Heeks et al. (2013) and Heeks et al. (2014) that conceptualise different levels of inclusiveness in innovation in process and outcomes. Heeks et al. (2014) provided a broader conception of inclusiveness by engaging in questions to identify who should be included and aspects of whether they be included in innovation outputs or innovation processes innovations. In their framework, Level 1 to Level 6 highlight the varied levels of inclusion based on needs, consumption (demand), adoption, and involvement of marginalised or excluded group (ibid):

Level 1: Intention-address the needs of the excluded group.

Level 2: Consumption-adopted by the excluded group.

Level 3: Impact-a positive impact on the livelihoods of the excluded group.

Level 4: Process-involvement of the excluded group in the development of the innovation.

Level 5: Structure-created within a structure that is itself inclusive.

Level 6: Post-structure-created within a frame of knowledge and discourse that is itself inclusive.

These six levels enable an instrumental tool to delve into inclusiveness both from the process and outcomes. I explore the inclusiveness of emerging AI and ML based PoC MedTech innovations in the Indian context by understanding – how inclusiveness is conceptualised in the emerging MedTech innovations in the Indian context. The emerging MedTech for the early detection of innovations provides an opportunity to understand the unmet needs and demand for cancer detection as a means to understand inclusiveness. I explore the inclusiveness of in MedTech innovations by understanding – how inclusiveness is conceptualised in the emerging MedTech innovations in the Indian context.

Scholars, including Chataway et al. (2014) argue the need to understand inclusive innovation in the ‘context of a holistic conception of the innovation cycle’ focusing on the various process and product innovations. In particular, understanding the roles played by the people in industrialising countries as both producers and consumers. It is thus pertinent to understand some questions that emerged from the literature: who are the producers and users of these innovations? Who are the innovators that are taking an interest in developing problem-solving innovations? It is pertinent to ask this question from an inclusion (and exclusion perspective) because of the dominant neglect of women as bottom-up innovators in the innovation literature (Cozzens & Sutz, 2014). Engaging with these questions would fathom understanding of factors that influence the development, diffusion, and adoption of the problem-solving role of innovations that aim to address unmet clinical needs, demand, and critical gaps in the healthcare delivery system in an affordable manner. As a first step, the literature draws attention towards importance of understanding evolutionary frame works to study innovation process using insights from evolutionary economics.

2.2. Lessons from existing framework to study technical change in industrial structures.

In studies of health systems and health economics, the dominance of neoclassical economics and market failure approaches have led to a static understanding of health innovation: in terms of technologies and products as input components of health systems and apparent market failures. To go beyond this static approach, studying concepts of inclusiveness from an evolutionary perspective is particularly valuable in the context of health innovations. In case of MedTech innovations, there has been a recent technical change in industrial structure that is catalysing these innovations. As a first step, the literature draws attention towards evolutionary frameworks. In this section, I review different frameworks studying influence of technical change in industrial structure using insights from evolutionary economics.

The pioneering work of Nelson and Winter (1982) enabled how to study the influence of technical change on industrial structure. They introduced an

evolutionary theory of economic growth that integrates appreciative (like historical accounts) and formal theorising of economic growth. They characterise technical advance as an evolutionary process, within which new technologies compete not only with one another but also the existing technologies in practice, considering two critical aspects (ibid):

- (i) Ex-ante uncertainty on which technology will prevail, highlighting the elements of uncertainty in technological evolution – which variety of technology will succeed?
- (ii) Ex-post selection determines which technology prevails and which does not in a given selection environment facilitated by many market environments.

Both the focussed market selection environment and systematic selection provide direction to technical advance, which works on both sides. Importantly, such evolutionary focus enables a dynamic analysis because industrial structures, technologies, the nature of competition, and key public policy issues change over time. The screening, selection, and implementation of new technologies is a time-consuming process. The selection mechanisms may involve new markets but may also involve non-market character, i.e., through institutions like firms/innovator strategies, government regulations, and STI policies. Therefore, evolutionary models of technological change provide a realistic way of understanding innovations vis-a-vis the neoclassical models that treated technology as exogenous (Edquist, 1997).

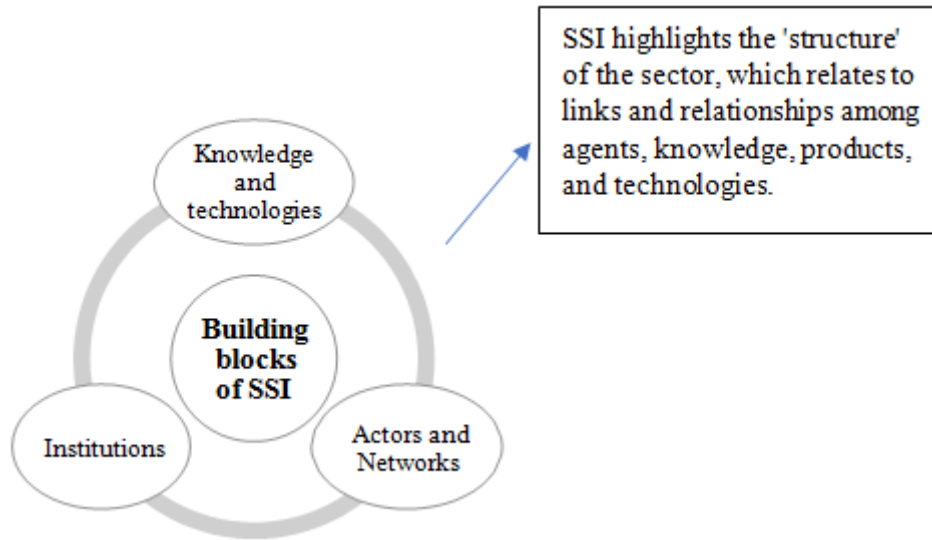
I reviewed various frameworks to assess the feasibility of studying technical change in the Medtech sector and inclusive innovations for the early detection of cancer. In addition to Nelson and Winter (1982), a range of other neo-Schumpeterian work in the 1980s, notably Freeman (1982, 1987), Nelson (1993), Lundvall (1992, 2007) paved the way for analytical frameworks that allowed building a richer understanding of innovation as a dynamic process. Mainly in analysing the instrumental role of innovation and learning in economic growth and development (Lundvall, 2007). This includes extensive work within the 'systems of innovations' (IS) approach belonging to the family of models forming evolutionary economics brought a departure from the linear view of technological progress. It defines innovation as an interactive process among a wide variety of actors. These include firm and non-firm actors (such as universities, government agencies etc.) and their actions shaped by institutions (Lundvall, 1992). IS approach highlights historical perspectives and learning as the key determinant of innovation (Edquist, 1997). Different boundaries of systems of innovations are explored in the literature, depending upon the level of aggregation.

The first notion was articulated in the form of national systems of innovation or NSI (Freeman, 1987; Lundvall, 1992; Nelson, 1993). The primary conception of

the NSI approach focussed on national boundaries, in which technological change and innovations are driven by a complex set of relationships among actors producing, distributing, and applying various kinds of knowledge (OECD, 1997). The actors mainly include organisations (private enterprises, universities, public research institutes, governments) and individuals (ibid). The regional systems of innovation approach focus on regional boundaries of innovation systems. This approach combines innovation research and regional science systems to explain the locational distribution and policy impact of regional innovation processes (Cooke et al., 1997; Asheim & Isaksen, 1997). While these frameworks are well accepted in global policymaking, there are concerns about their applicability in industrialising economics (discussed later in the chapter). Some efforts have been made to benefit from the spatial dimensions of the above frameworks, in developing more localised systems, for instance, the Local Production and Innovation Systems (LIPS) approach (Cassiolato et al., 2008). LIPS was developed by RedeSist, a Brazilian research network, with a broad approach of NSI to study local processes of production, innovation, and knowledge accumulation and how to mobilise them in the Brazilian context (Cassiolato & Lastres, 2020). Going beyond the geographical boundaries, the framework of technological systems focuses on specific technologies and participation and interaction of dynamic agents to drive economic growth (Carlsson and Stankiewicz, 1991). However, while all the frameworks focussed on the development and diffusion of new technologies, none of these provides a lens to study inclusiveness.

Due to the study's strong component of sectoral innovations, I reviewed the sectoral systems of innovation approach, SSI (Malerba, 2005; Malerba and Mani, 2009). The SSI approach enabled development of the initial framework to undertake an in-depth study of inclusive innovation in India's Medtech sector. Inspired by evolutionary theory and IS approach, the SSI approach (see figure 1) focuses on the rate and type of innovations and innovative activities in sectors (Malerba, 2005), with 'learning' as a critical determinant of innovation. SSI consists of the knowledge base, technologies, inputs and potential or existing 'demand'. 'Knowledge base, technologies and inputs' define the nature of sectoral boundaries and influence the behavior and organisation of firms (ibid). The 'actors and 'networks' are characterised by specific learning processes, competencies, organisational structures, beliefs, etc. They comprise individuals (consumers, doctors, scientists, etc.) and organisations at numerous levels of aggregation, such as firms (users, producers, suppliers) and non-firms (universities, regulatory agencies, trade associations) (ibid).

Figure 1: Three main building blocks of SSI



Source: Malerba, 2005

Further, SSI focuses on supply and demand, wherein demand is not merely an aggregation of a set of similar buyers but composed of heterogeneous agents whose institutions shape interactions with producers. These agents are connected through various market and non-market relationships and interact - - 'through 'sector-specific processes' of 'communication, exchange, cooperation and' command'- to create, develop and diffusion new sectoral products (ibid; Malerba and Mani 2009). Moreover, institutions that shape interactions include rules, standards, regulations, established practices, etc., some are specific to the sector, and others are national institutions bearing different impacts on innovation in different sectors and countries. This aspect of SSI allows us to study institutions relevant to the sector, even in assessing the roles that local, national, and global institutions play in the innovation process of a particular sector. Hence, the process of change and transformation in the sectoral system involves the co-evolution of several elements involved. In this sense, SSI departs from NSI, as NSI facilitates the study of innovation systems at a national level. SSI helps build an in-depth understanding of sectors with the boundaries of the innovation process in local, national, and global dimensions - which often co-exist in a sector. SSI also allows for flexibility while selecting the unit of analysis and variables depending on the level of detail of the study. SSI approach facilitates descriptive analyses of the innovations, dynamics of the Indian MedTech sector, and the nature of innovations that emerge through interactions among knowledge, actors, and institutions. It provides a systemic perspective on science, technology, and innovation in health.

However, it is not a complete framework to study of inclusive health innovations in India (and LMICs) for the following reasons:

- (1) There are concerns with the 'ex-post' conceptions associated with the systems approach, i.e., the systems approach is mostly built on empirical findings of the global north or the industrialised countries. On the contrary, it is an 'ex-ante' concept in the global south as socioeconomic behaviour concerning innovation is not always systematised (Arocena and Sutz, 2002). Moreover, innovation system frameworks highlight selective policy instruments that benefit a small group of firms and do not have a nationwide impact (Altenburg, 2011). Applications of SSI in sectors of LMICs, including the Indian pharmaceuticals sector, have been explored by some scholars (such as Chaturvedi, 2007; Malerba and Mani, 2009). However, there is a need to delve deeper into the complex linkages of local health needs and demand and institutional framework in influencing sectoral innovations. Such linkages are crucial to understand new-age health innovations in India.
- (2) Studies suggest that to channel government interventions towards the production of innovations in specific areas, it is imperative to have a deeper understanding of demand and supply influences that motivate innovation process at the level of industry and firms (Mowery and Rosenberg, 1979; p 103). Further, IS approaches do not allow for an evolutionary understanding of demand in resource-constraint settings of LMICs, which is important for developing and introducing need-based innovations (Heeks et al., 2014). While the focus of policies based on systems of innovation approach is often to boost supply-side institutions, the significance of collective demand facilitating the diffusion of health technologies as the buyers are a mix of individuals (individuals, doctors, and organisations like government, hospitals, clinics) is often undermined (Andersen and Johnson, 2015; Srinivas, 2012). The IS literature does not comprehensively discuss the market varieties that shape the diffusion of health innovations in LMICs (Altenburg, 2009). In health innovations, mapping demand remains particularly important because a range of actors, co-evolving institutions, politics, and policies play an instrumental role instead of solely relying on price signals and market dependence (as in traditional economics). This is true for industrialising economies like India, where technological advances are built rapidly on the supply side to 'catch up', while demand remains vaguely defined due to its heterogeneous and complex nature. There is a need to adequately study the concept and influence of demand in innovation generation in innovation studies, whilst existing literature mainly highlights sectoral advances and technological investments created by supply-side institutions (Srinivas, 2014). This is particularly true in our case in point - health innovations.

The concept and influence of demand in innovation generation have not been adequately studied in the innovation studies; much of the literature – including NSI and Schumpeterian and neo-Schumpeterian frameworks – mainly highlights sectoral advances and technological investments created by supply-side institutions (Srinivas, 2014). In health innovations, mapping demand remains particularly challenging because, beyond the price signal and market dependence fixation of traditional economics, it is influenced by a web of actors, including institutions, politics, policies, and evolutionary processes. It is interesting to note that in the absence of a defined innovation policy, strategic demand-led policies and national welfare regimes play an immense role in determining the nature and rate of innovations. The policies have the potential to transform needs into demand to create new markets (Srinivas, 2012).

The state faces significant challenges associated with the sustainability of the health care system, particularly while fulfilling the health goals and maintaining the viability of the industry. In this process, the state engages with several stakeholders with conflicting interests to match demand into several supply-side institutions. Boon et al. (2011) highlight that ‘intermediary user organisations’ can be critical in demand articulation and influence emerging technologies. They suggest that targeting the governing process to heterogeneous actor groups with coordinated roles and strategies influence more demand-oriented policy push for innovations for businesses and users. Public procurement has been suggested to enhance markets for new and existing technologies by shaping the demand environment (Chataway, 2016; p245). Several scholars have offered intermediation of demand and supply through public procurement of innovation (Edler and Georghiou, 2007; Uyarra and Flanagan, 2009; Kattel and Lember, 2010; Edler and Yeow, 2016). These studies have shown how public procurement differs according to the nature of the innovative product and disruptions caused by different types of innovations in the practices of buying organisations. Instrumentalising demand can be a very important source to instil ‘access’ to innovations. These concepts are not adequately dealt with in the systems approach.

- (3) Institutional variety in India (and LMICs) is much broader than rules, laws, standards, regulations, and established practices and comprises a mix of formal and informal particularly in the health sector in LMICs, are influenced by a range of complex institutions and are not abstracted from ethical norms and moral and political values (Papaioannou and Srinivas, 2019). Moreover, in the absence of a defined innovation policy, the strategic demand-led policies, national welfare regimes and the political economy around the health sector play an immense role in

determining the nature and rate of innovations and have the potential to transform needs into demand to create new markets (Srinivas, 2012).

- (4) The innovation systems literature does not allow the incorporation of complexities of delivery mechanisms in LMICs. Scholars like Ramani et al. (2012) highlight that the role of various actors in the effective diffusion of innovation hinges upon a complex network of actors (including funding agencies, facilitators, service providers, and field staff) that closely interact with the target population. Specifically, in terms of health innovation, Angeli and Jaiswal (2016) highlight that sustainable business models for health care delivery in India is an under studied domain. They emphasise that sustainable business models involve 'co-creation of patient needs, community engagement, continuous involvement of customers, focus on human resources for health, strategic partnerships, economies of scale, and cross-subsidization' (ibid; p 498).

Some of these limitations are addressed in the framework introduced in the qualitative institutional heuristic to study health care by Srinivas (2012). Srinivas (2021) explains that heuristics are handy dynamic 'thought experiments' to study complex problems. The heuristic involves a co-evolving institutional triad of health care, which comprises (1) industrial production of health innovations, (2) provision of health care delivery, and (3) consumption (demand) of health care through individual or collective buying systems. One can picture these three vertices (see figure 2) as constantly evolving, and countries require consistent efforts on all three institutional fronts. The variability of the three domains of the triad helps in analysing institutional and organisational variety assisting health systems. This serves as a broad guide to how policies can guide the production of context-specific and inclusive innovations. It suggests that countries that are assumed to be at similar developmental stages or industrial features may exhibit different interactions between the three evolutionary domains of the triad (ibid).

The heuristic goes beyond the traditional health economics concepts of market failure in public goods. It does so by offering a richer approach to studying technological advances in the health sector and the complex process of planning, institutional change and historical characteristics of knowledge and theories of change (Srinivas, 2020). The qualitative heuristic of the institutional triad has been used for inter-country comparisons for markets for medicines, vaccines and, more recently, COVID- 19 test kits (Srinivas et al., 2020). However, the difficulty of separating delivery from consumption in healthcare industries is one of the key areas where the application of heuristic calls for caution.

Figure 2: Institutional triad of healthcare



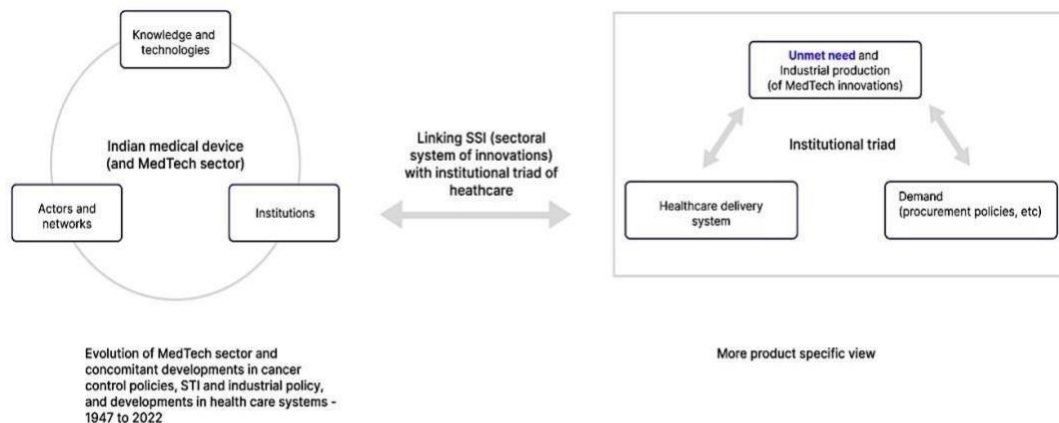
Source: Srinivas (2012).

This paper proposes that combining SSI with qualitative heuristics allows for a more nuanced understanding of the development of inclusive MedTech innovation and its adoption in the health care delivery system.

2.3. Introducing IHI framework to study inclusive MedTech innovations for cancer

The IHI framework (see figure 3) proposed in this paper combines the elements of SSI and the institutional triad of health care to present a compatible framework to study emerging health innovations that are mainstreaming inclusivity in LMICs.

Figure 3: Inclusive Healthcare Innovation framework



Source: Authors' adaptation of SSI and triad to contextualise industrial production of health innovations and its adoption.

IHI framework uses SSI for a deeper understanding of all components of the sectoral ecosystem, which goes beyond any product or innovation. To outline briefly, the SSI approach is valuable in understanding sectoral developments due to its foundations in

- (1) evolutionary theory, which places dynamics, process, and transformation at the centre of the analysis, and
- (2) the innovation systems approach, which considers innovation as an interactive process among a wide variety of actors (Malerba, 2005). It

suggests that various factors influence innovation and production in a sector (Malerba & Mani, 2009), including:

- (a) firm-specific variables, which are learning and capabilities, R&D, production investments, strategies, and organisational structure, and
- (b) broader knowledge and technologies that categorise a sector, links with other sectors, the role of actors (competitors, suppliers, users, universities, financial organisations, public agencies, and government), and demand characteristics and types of institutions. Thus, it enables conceptualising inclusiveness in the MedTech sector in India, which is rapidly gaining technological capabilities. These technological capabilities are driven by advanced computing technologies, including AI and ML.

On the other hand, the institutional triad of three domains – industrial production, demand, and healthcare delivery – help in defining the linkages between health and industrial policies. They show these linkages by pointing out the strong role of these domains in the development of health sector performance and industrial growth. However, the cumulative interactions between these three domains are often neglected in health system research and industrial policy analysis. The co- evolutionary triad domains facilitate understanding the role of technological advances and problem- solving innovation in bridging the gap between industrial concentrations and health deprivation (Srinivas, 2012, 2016, 2020). They reconceptualise the roles of health planning and developmental state to take cognisance of technical advances rather than merely taking them as given. This element guides policies, institutions, and market varieties to showcase the compatibility (or not) of MedTech innovation for early detection of cancer with the health care delivery system to address prevailing needs. To capture these needs in the framework, I have introduced a new element of ‘unmet need’, which is crucial to study on inclusive innovation. The institutional triad helps engage in the development complexities of the health sector due to the co-evolution of three institutional domains, underscoring a combinatorial notion of how multiple institutional effects can occur at once and change as well (Srinivas, 2020):

- (1) **Unmet needs and industrial production of health innovations:** This element of the triad entails development of industrial capacity and production elements using knowledge exchange, technological learning, testing, prototyping of technological solutions (Srinivas, 2012). To add an inclusiveness dimension, I added capabilities to frame and solve unmet needs by explicitly defining it for local context. Adding ‘unmet needs’ along with industrial production in institutional triad emphasizes a specific kind of capacity to develop innovation and production capability that are relevant for both industrial development and health services. This element of the triad engages with STI and industrial policy

by Ministry of Science and Technology, Ministry of Commerce and Industry, Ministry of Chemicals and Fertilizers, AI related policies, impact capabilities to develop AI and ML based PoC Medtech innovation, supporting development of context specific solutions for early detection of cancer for low resource healthcare settings.

- (2) **Provision of health care delivery:** This domain of triad involves health policy instruments that channel actors through which innovation can be adopted in the healthcare system, including primary and community health centres, private and public hospitals, clinics, diagnostics provider.
- (3) **Demand of health care:** This triad domain focuses demand through individual or collective buying systems, including procurement policies (also see discussion demand in Chapter 3). Another critical aspect is an evolutionary understanding of the emergence and transformation of demand which plays a significant role in the dynamics and evolution of healthcare innovation, as it includes individual consumers, firms, and public agencies, each characterised by knowledge, learning processes, competencies and goals and affected by social factors and institutions.

The IHI framework facilitates understanding of the seriously deficient industrial and health system linkages in developing and adopting emerging inclusive innovation in LMICs. It does this by providing an alternative approach to understanding the inclusive innovation in India that aim to fulfil unmet health needs and focus on improving quality of life. The aim is to nudge interest groups and policymaking institutions such that inclusive innovation may, in turn, become a new goal for innovation efforts (as introduced by Arocena and Sutz, 2016). To support this, IHI framework is to be viewed as an evolving approach to studying inclusive health innovation at large and a step in searching for alternatives by focussing on local context and health needs. It provides a bottom-up approach to link unmet needs with the industrial production of innovations for the early detection of cancer in low-resource health care settings.

3. Research methodology

This paper focuses on India as the research setting for several reasons. First, oral, breast, and cervical cancer are among the leading causes of death, and, at present, the coverage of public screening is low. While the treatment of cancer is expensive, there are huge concerns over the availability and access to affordable and appropriate medical devices and diagnostics that could substantially reduce the cost of the treatment. Second, according to the Constitution of India, 'health' is a State subject in India, i.e., whilst national policies provide an overarching framework, states have the prerogative of implementing health-related matters, including cancer. Therefore, the one-size-fits-all approach does not work for the Indian health system and allows for

studying various comparable scenarios across states. Third, in recent years, there has been a surge in MedTech innovations that mainstream inclusiveness. This gives an opportunity to study the institutional bundle that channelled this inclusiveness. This is important because historically coherent STI and industrial policy have been missing or neglected health goals.

This paper used a multiple case study research design which is the preferred research strategy when researching an under-researched topic (Yin, 2017). It comprises a qualitative data collection methodology for an in-depth investigation of inclusive MedTech innovations for the early detection of cancer within its real-world context. Given the data collection of this research was done in the peak of COVID-19 pandemic, it was not feasible to conduct face to face fieldwork. This paper uses qualitative research methods comprising archival and policy document reviews, online-structured research interviews, and a range of secondary data sources.

I reviewed archival data and documents and conducted online semi-structured interviews with various interest stakeholders, including policymakers, heads of key industry associations, venture capitalists, and incubators. This facilitated deeper insights into the landscape of MedTech innovations for cancer in India. I further corroborated the data using non-traditional secondary sources, including podcasts, Twitter space, Instagram live, online conferences and webinar participation. These data helped identify three cases of MedTech innovations offered by start-up firms, for the early detection of cancer in India (see table 2):

- (1) **Thermalytix:** The novel solution uses a high-resolution thermal sensing device and a patented cloud hosted analytics solution driven by AI for analysing the thermal images. It is a portable, non- invasive, radiation-free, and no-contact solution that measures the temperature distribution on the chest to detect early-stage breast cancer accurately. This screening solution is offered by Niramai Health Analytix Private Limited (Niramai), a startup based in Bengaluru, Karnataka. The ethos behind application of AI and ML is based on mission of NIRAMAI, which is an acronym for ‘Non- Invasive Risk Assessment with Machine Intelligence’.
- (2) **OralScan:** This innovation is a non-invasive handheld screening device for oral cancer. It also assists the dental surgeon in performing a biopsy on the most appropriate site to confirm the diagnosis of malignancy. It is offered by Sascan Meditech Private Limited, a start-up based in Kerala. OralScan uses a twofold mechanism of an optical system which comes with a multispectral imaging technology based hand-held device and tablet which facilitates tissue analysis via customised software based on ML algorithms.

- (3) CervAstra: CervAstra, is a computational pathology-based point-of-care cervical cancer detection system offered by Aindra System Private Limited, a start-up based in Bengaluru Karnataka. CervAstra analyses pap smear (cells from the cervix) samples using a computational pathology platform to examine and detect normal or abnormal cells within a few hours with minimal human intervention, compared to other devices, which are expensive and take a longer time.

Table 2: Brief case description

Early detection of cancer (type)	Case study Innovation (market launch)	Start-up firm	Description of innovation	Key characteristics
Breast cancer	Thermalytix (2017)	Niramai Health Analytix Private Limited (Bengaluru, Karnataka, India)	High resolution thermal sensing supported by patented AI algorithms to detect abnormal thermal patterns to detect early-stage breast malignancies.	○ Founder's personal motivation due to lived experiences of cancer in family. ○ Early-stage funding from private sector along with government incubation and accelerator support ○ Clinically validated novel technology ○ For women of all ages ○ Radiation free, non-invasive and privacy aware ○ Scalable to both urban and rural areas of India with basic training to health workers ○ Aims to make early detection affordable by offering different business models
Oral cancer	OralScan (2020)	Sascan Meditech Private Limited (Thiruvananthapuram, Kerala, India)	Handheld optical imaging multimodal device, along with cloud-based ML algorithms for realtime feedback on tissue status,	○ Founder's personal motivation due to lived experiences of cancer in family. ○ Early-stage funding from government. ○ Clinically validated novel technology ○ Breakthrough technology as very few precise

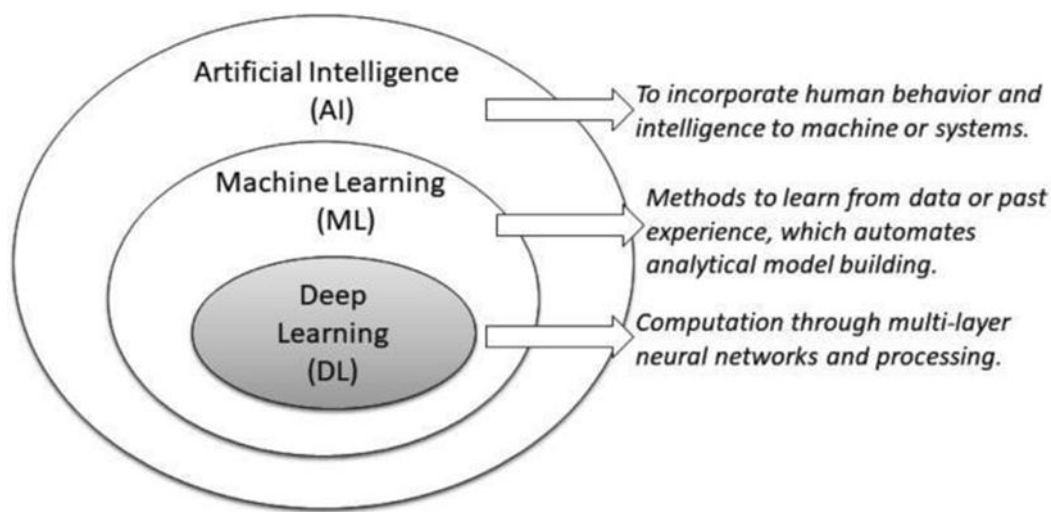
			and early detection of precancerous lesions of the oral cavity.	technologies are available to screen and early detect oral cancer, and biopsy guidance. ○ Eliminates subjectivity in early detection vis-à-vis existing technology. ○ Non-invasive and radiation free ○ Scalable to both urban and rural areas of India with basic training to health workers ○ Aims to make early detection affordable by offering different business models
Cervical cancer	CervAstra (2020-21)	Aindra Systems (Bengaluru, Karnataka, India)	Computational pathology system improving papsmear cytology	○ Founder's personal motivation to democratise advanced computing technology. ○ Early-stage funding from government. ○ Clinically validated novel technology ○ Non-invasive and radiation free ○ Eliminates subjectivity in early detection vis-à-vis existing technology. ○ Scalable to both urban and rural areas of India with basic training to health workers ○ Aims to make early detection affordable by offering different business models.

Source: Author's presentation of case studies.

The cases present similarities and differences in the innovation process in the same selection environment. I identified these cases based on the following broad criteria. First, cases reflect point of care innovation designed to fulfil unmet needs of the screening and early diagnosis of breast, cervical and oral cancer, which are not met by existing technologies. All the case studies offer solutions that are conducive for the India healthcare system settings. Second,

these cases are driven by the personal motivation of lead innovators and their strong problem-framing and solving skills to respond to challenges of early detection of cancer in low-resource healthcare settings of India. Third, all the cases have a ML and AI based component along with a hardware component, reflecting a change of trajectory of innovation in a sub-sector of import dependent medical device sector. These innovations are a result of technical change in the MedTech sector due to the affordable availability of high computing technology, artificial intelligence and its subsets, machine learning and deep learning. Figure 4 shows how AI, and its subsets use data to identify complex patterns that humans find difficult to comprehend and notice.

Figure 4: Illustration depicting the role of AI and its subsets.



Source: Sarker (2021, p3)

The second phase of primary data collection involved online semi-structured interviews with the lead innovators of case studies through online semi-structured interviews, online conferences, and workshops. The data from innovators were triangulated by interviews with clinical research scientists, biomedical engineers, and incubators.

The data was transcribed and coded both manually and using NVivo 12. In a departure from firm level analysis, this paper used PoC Medtech innovations for early cancer detection as the unit of analysis. The primary aim in doing so is to capture the various nuances of understanding unmet needs and inclusions by understanding their development, diffusion, and adoption process. Studies have also acknowledged the need for going beyond 'firm' as a unit of analysis to understand wider dynamics of innovation in which firms are a part of the innovation process but not central to it (for instance, Altenburg 2011). Further, analytical techniques, including thematic codes based on the IHI framework, are used for analysing empirical evidence. Both pattern matching and coding strategies were used to understand the role of health, science and technology,

industrial policies, and related institutions in shaping inclusive innovations for early cancer detection in the Indian MedTech sector.

4. Lessons from case studies analysis

Applying IHI framework to the case studies, I found a set of actors that have coherently emerged to form an organic MedTech ecosystem facilitating a space to innovate in a space where the public sector is virtually non-existent. These actors include policy actors, private innovators, incubators, and accelerators. Primarily the role of two actors have been instrumental. First, government funding (mainly Department of Science and Technology and Department of Biotechnology) and incubation have played a critical role in fostering the early stages of the development of innovation. Government endorsement and support during all stages development process has signalled confidence in the private sector. Second, the emergence of private non-domain innovators. Table 3 profiles the non-domain lead innovators and founders of the start-up firms that are offering Medtech innovations. It shows how educational background, work experience, and multidisciplinary collaborations played an instrumental role in problem-framing and solving.

Table 3: Profiling of non-domain lead innovators

	Educational background of lead innovators	Work experience	Interdisciplinary collaborations
Thermalytix	- University of Visvesvaraya College of Engineering, Bengaluru - Indian Institute of Science, Bengaluru	Research leadership role in Hewlett Packard Limited and Data Analytics Research Laboratory, Xerox Research Centre India	Worked with radiologist and thermographer, clinicians, and hospitals.
OralScan	- Sree Narayana College, Kollam, Kerala - Cochin University of Science and Technology, Kerala	- Centre for Earth Science Studies, Trivandrum, Kerala - Marie Curie and DAAD fellow - Research roles in biomedical startups	Collaborated with dental colleges, researchers, and biomedical engineers to apply physics to oral cancer screening
			Collaborated with clinical researchers, biomedical engineers to apply physics to cervical cancer screening

CervAstra	○ Scientist, Centre for Earth Science Studies, Trivandrum, Kerala ○ Indian Institute of Management, Bengaluru	○ Software engineering roles at Infosys, Lucent Technologies, and Wipro Technologies	Partnered with IIT Mandi, IIT Chennai, for hardware and software, Kidwai Memorial Hospital to understand challenges of cervical cancerscreening.

Source: Author's data analysis.

The lived experiences of cancer among family members of these innovators and intention to drive societal change emerged as a key driver in the development of scalable solutions to address challenges of early detection of cancer in resource constraint settings. This brings an important insight from the inclusiveness perspective, in which large MNCs are not the sole producers of innovation as policies recognise these individual innovators (e.g., through BIRAC's programmes and Start-up India policy).

The analysis found that in each case, inclusiveness is conceptualised in both process and outcomes through effective problem-framing of layers of unmet needs. It is done by spelling out otherwise assumed unmet needs in the early detection of cancer in a limited healthcare capacity. As shown in table 4, in terms of process, the case studies highlight that inclusiveness in innovation is driven in following ways:

- (1) Inclusiveness in innovation is achievable in resource-constraint settings with the affordable applications of high technology.
- (2) Inclusiveness is incorporated by framing unmet needs of the early detection of cancer in low resource healthcare settings.
- (3) Inclusiveness is incorporated by involving users, clinicians, radiologist, in the design process to address unmet needs.

Table 4: Understanding inclusiveness in process of innovation

Innovation	Inclusiveness in innovation process drivenby	
	identification of unmet needs	including users in design process
Thermalytix	o Low sensitivity of mammography, women under the age of 45 years and/or women with dense breast tissue.	o Senior radiologist and expert thermographer
	o Inadequate health infrastructure, and high cost of mammography machine. o Shortage of qualified human resources.	
	o High cost of mammography exam. o Cultural issues associated with touch-based screening methods. Radiation and pain in mammography.	
OralScan	o Lack of objective modalities for early detection of oral cancer.	o Clinical researchers, Dentists, and PhD researchers
	o Shortage of clinicians.	
	o High cost of adjunct technologies.	
	o Shortage of clinicians and pathologist	
CervAstra	o Shortages of pathologists in resource constraint settings.	o Pathologist and clinicians
	o High cost of pap smear test.	

Source: Author's analysis of data.

The analysis reveals that historically there has been a lack of strong motivation to drive inclusive innovation in the medical device sector. Nevertheless, the AI and ML surge in the fourth industrial revolution has substantially increased the scale and scope of inclusive innovation in the MedTech sector in India. For instance, the case studies of the thesis highlighted how PoC Medtech innovations leverage the spillover effects of these advances in AI and ML to screening and early diagnosis of breast, oral, and cervical cancer in resource constraint settings. They do so mainly in two ways (i) by introducing novel screening modalities minimising subjectivities in the early detection of cancer and (ii) by making existing modalities conducive to low-resource healthcare settings of India. This finding contributes to the under-researched area of conceptualising inclusiveness in high-technology health innovations developed in resource-constraint settings of LMICs.

To some extent, reverse innovation captures the role of LMICs as producers of high-technology innovations (Immelt et al., 2009). However, it is found to be conflating with other terminologies (like frugal innovations) and limiting policy implications due to innate assumptions about the scaling-up and flow of the markets from industrialising to industrialised (for instance, Harris et al., 2016). Traditionally, innovation and development studies have conceptualised

the inclusive character of innovations in resource-constraint settings with a focus on frugality (low-technology solutions) or grassroots (being low-cost products/services driven by communities) (also discussed in Chapter 3). Even in the Indian context, recent studies highlight frugality as the essence of innovations (Bhaduri & Bhattacharya, 2021). A recent study also analyses the development of medical devices from innovative manufacturing firms in South Africa. However, it uses a frugality lens (Chakravarty, 2022). The findings of the thesis align with these studies in so far as highlighting the need for locally relevant solutions is concerned. The results of this thesis mark a departure from the traditional reference to the innovations in resource constraint settings in the literature. Such distinction between frugality and inclusive innovations is also explored by Onsongo and Knorrnga (2020).

Table 5: Applying AI and ML in early detection of cancer in low resource settings.

Innovations	Which existing modality is being improved?	What are its challenges?	What is the novelty in the PoC MedTech innovations?		How high technology invoke inclusiveness ?
			Hardware component	Software component	
Thermalytix	oThermography	O Multiple temperature points, difficult to interpret and analyse for human eyes.	o High resolution thermal camera	o Uses cloud-based ML solution to analyse different temperature points of thermal images	- o Making thermal imaging conducive for low resource settings by applying ML to analyse and extract more than 120 features from the image. - o Give an objective score to identify whether a person is likely to have breast cancer.

Oral Scan	o Visual inspection of oral cavity	o Involves subjectivity, no biopsy guidance, and shortage of clinicians.	o Multimodal LED camera	o Uses cloud-based ML solution to analyse images for peaks of collagen and oxygenated haemoglobin absorption.	o Making available an objective early detection modality conducive for low resource healthcare settings by real-time identification potentially malignant sites; and biopsy guidance(if needed)

Source: Author's analysis of data.

Secondly, the analysis highlights inclusiveness by identifying and stating unmet needs for early cancer detection in low-resource healthcare settings. The founders (lead innovators) were motivated by lived experiences of the pain and difficulties of cancer in family and friends. This experience enabled the innovators and their team to state and unravel the following layers of unmet needs of early detection of cancer in low-resource settings, which are otherwise un-spelt.

- *Need for early detection modalities that mitigate limitations existing screening and early diagnosis modalities.*
- *Need to address larger systemic challenges of limited healthcare capacity, in form of shortages of health care staff (doctors, radiologist, and pathologists).*
- *Need for affordable and non-invasive screening modalities due to lack of financial coverage for expensive gold standard tests, mainly in rural areas in India.*

The analysis points out unmet needs due to challenges both with the gold standard and low-cost screening modalities available for the early detection of breast, cervical, and oral cancer. For instance, in the case of breast cancer, there is no conducive modality for women of all ages and women with dense breasts. Mammography is suitable for women above the age of 45 but not younger age groups and women with dense breast tissue. Ultrasound is for younger women but is not a practical option for screening in resource constraint settings. In the case of oral cancer, there are concerns about the subjectivity of clinicians involved in visual inspections, which increases the chances of wrong biopsies. In the case of cervical cancer, in addition to the subjectivity of screening methods and infrastructural challenges with pap smear screening. All case studies acknowledge the cost concerns shortages of doctors, radiologists, and

pathologists, and infrastructural gaps in using gold standard modalities. These healthcare challenges make low-cost screening techniques used by government screening programmes also prone to subjectivity.

To incorporate these needs into the design of innovations, the analysis showcases the application of design thinking by innovators and their teams. Design thinking is a problem-solving approach that focuses on understanding the needs of the user (for instance, see Oliveira et al., 2022). In all the case studies, this has been done by understanding unmet clinical needs by involving clinicians, pathologists, and radiologists in the prototype development process. The degree of user involvement in customising the process of innovation plays a key role in democratising innovation (as discussed in von Hippel, 2005). In reference to this thesis, democratising means a step to gain broader acceptability in clinical practice.

In terms of outcomes, as highlighted in table 6, the case studies show the following signs of inclusiveness:

- (1) Inclusiveness showcases availability and access to non-invasive, portable, point of care, easy to use early detection modalities of cancer in low-resource healthcare settings. For instance, femtech for early detection of cancers affecting women.
- (2) Inclusiveness in women as innovators in resource constraint settings.
- (3) Inclusiveness of the end users (beneficiaries) not just as receivers but contributors to improving technology.

Table 6: Understanding inclusiveness in outcomes of innovation

	Outcomes of innovationprocess
Innovation	Addressing needs
o Thermalytix	- o Early detection femtech for women (and men) of all ages, and breast type. - o Clinical validation studies in Indian population. - o Radiation free, pain free, and no touch. - o Portable, compact, and point of care modality. - o Low hardware cost vis-a-vis mammography machine. - o Easy to use with minimal training. - o Variety of business models aimed to increase affordable access. For instance, INR1000 - INR 1500 in hospitals and clinics, and INR 100 -150 low-cost version for rural settings.

o OralScan	- o Objective and effective screening and diagnosis using technology. - o Clinical validation studies in Indian population. - o Portable, compact, and point of care modality. - o Easy to use with minimal training. - o Lower per patient screening cost - o Variety of business models aimed to increase affordable access.
o CervAstra	- o Early detection femtech using computational pathology provides results within fewhours. - o Clinical validation studies in Indian population. - o Portable, compact, and point of care modality. - o Variety of business models aimed to increase affordable access. Price per test is INR200 – 400.

Source: Author's analysis of data.

First, by bringing a concerted focus on point-of-care technologies for female health (Femtech), mainly in screening and early cancer detection, which has historically been neglected in the Indian context (for instance, Parez, 2019). Thermalytix provides effective solutions for breast cancer screening for women of all ages, a characteristic missing in the gold standard modality (mammography), which is only suitable for women over 45 years. Moreover, the innovation provides no-touch screening in separate screening rooms. It thus acknowledges the sociocultural sentiments towards touch-based screening in many women in the Indian context. CervAstra has expedited and improved the traditional pap smear cervical cancer screening for low-resource healthcare settings. It does so by using an AI-based computational pathology system, enabling faster results at the point of care. OralScan enables both objective screening and biopsy guidance for oral cancer in low-resource healthcare settings.

In all case studies, the easy-to-use design of innovations leverages technology to trickle down innovations in remote and rural areas in India where there is a lack of clinicians, health care professionals, and infrastructure to conduct screening. These innovations' compact and portable nature increases their reach beyond the diagnostic centres and hospitals in urban settings, facilitating point-of-care access to rural healthcare settings. They do so by eliminating the need for space, capital expenditure, and infrastructure required to maintain and operate large machines and apparatus (required in mammography, MRI, etc). These innovations are designed to be used with limited training for frontline workers of primary health centres or community health centres in rural and resource constraint settings. Such point-of-care availability offers usefulness in community settings with large-scale screening. Moreover, it also offers reduction in operational time and screening logistics as compared gold standard modalities. All case studies use several business models targeting

different populations. These business models consider where the screening is provided, including rural or urban health care settings, public or private hospital or clinics, diagnostics providers, screening camps. This facilitates options of availing the same technology at a lower cost. Therefore, high-technology innovations are meant for not just poor but for a wider range of users. This user base is expanded from just poor or rich to include the 'missing middle' population, which lacks coverage under any kind of health insurance in both rural and urban areas (Sarwal et al., 2021).

Second, the analysis reports the increased role of women in the innovation process in these cases, for instance, lead innovator and entrepreneur (Thermalytix), and consulting pathologists and clinicians (CervAstra). These insights are important as previous studies suggest a lack of recognition of women as bottom-up innovators in the literature (for instance, Cozzens and Sutz, 2014). The finding aligns with BRI and SII conceptualisations of inclusiveness in so far as understanding the role of industrialising countries as a producer and users of innovation are concerned.

Third, the analysis of inclusiveness by the involvement of end users in technology development and improvement. It is a unique feature that reimagines technological development in healthcare. These case studies have a software component based on trained and tested ML algorithms that facilitates the screening and early detection results. ML algorithms continue to learn and update their models as new data is collected and processed with more use of these PoC Medtech innovations. Therefore, it is an unintended but prominent inclusion of the beneficiaries in improving technological capabilities of cancer screening and early diagnosis. However, this aspect of inclusiveness needs to be supported by strong regulations on the ethics of data collection, privacy, and storage.

5. Advances in conceptualising inclusive innovation and policy considerations

In this paper, I proposed a novel IHI framework to study technical change in the MedTech sector with a lens of inclusiveness. There are few scholars who study the technical change in the health sector, for instance, Reich, 1990; Gelijns et al, 2001; Kaplan & Laing, 2005; Srinivas, 2012; Shadlen & Fonseca, 2013; Mackintosh & Tibandebage, 2016; Mackintosh et al., 2018). Using IHI framework, this paper brings a nuanced conceptualisation of inclusiveness by linking unmet needs of the early detection of cancer with industrial production of innovations and health care delivery systems in resource constraint settings.

In terms of applicability of emerging evidence and insights, the policy implications on inclusiveness of innovations are valid for both resource constraint and industrialising LMICs, and industrialised countries. Mainly in the post-pandemic context, the role of inclusiveness has gained prominence in

enabling sustainable health and industrial systems. Using the IHI framework, the findings of the paper connect academic endeavour with policy and practice. They do so by (a) understanding the sectoral indicators that can strengthen both health and industrial efforts for better outcomes for cancer care and (b) framing how new technologies can integrate in the inclusive health agenda, including Sustainable Development Goals 2030. Recent Parliamentary Committee Report provides some signs of creating more public demand by integrating the new MedTech innovations in a larger decentralised diagnostic plan. This plan can systematically decentralise and incentivise the innovations and competition in this space in both urban and rural areas under PMJAY (Rajya Sabha, p172). Furthermore, as emerging MedTech innovations extensively use AI and ML, there is a need to curate effective regulations on data storage and data privacy medical innovations that use advanced computational technologies. I conclude with an optimistic and cautious perspective for the role of technology in the early detection of cancer in low-resource settings. It is essential so that the benefits of the technology advancement can be reaped in an ethical manner.

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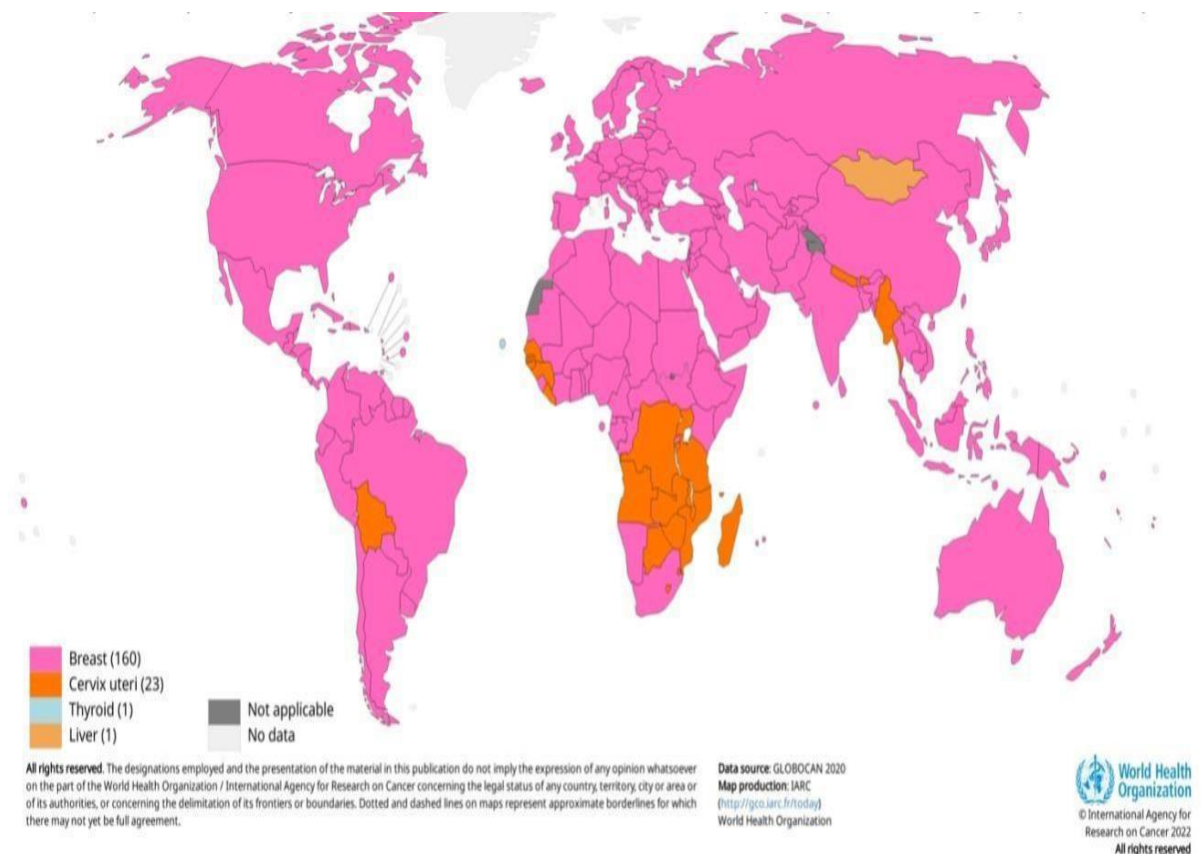
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Appendix

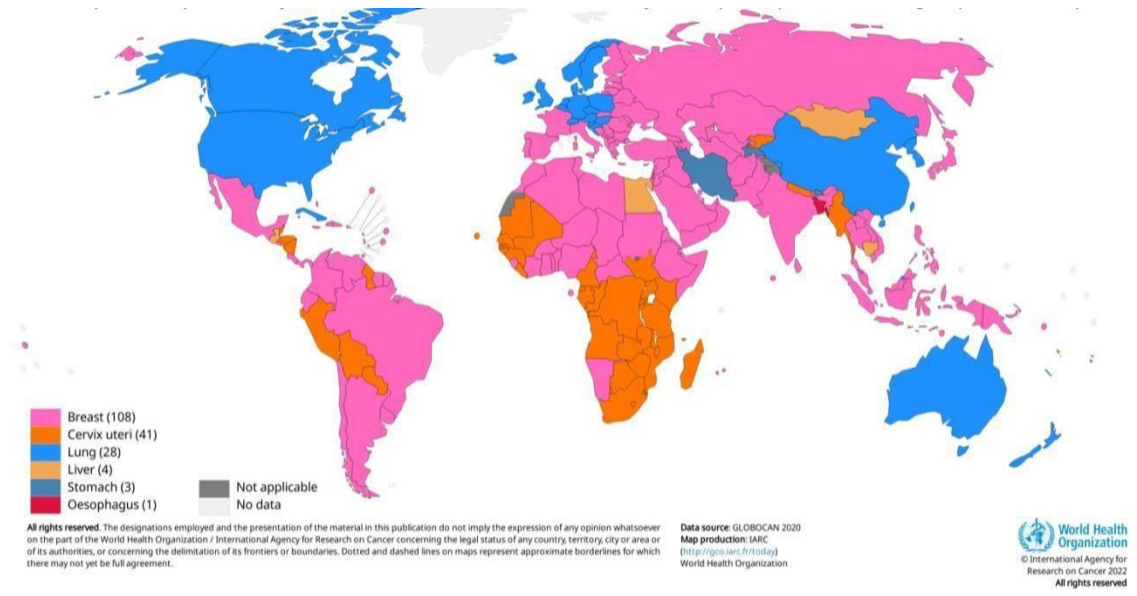
Appendix A.1: Country-wise estimated age standardised incidence and death rates, females

Figure 1a: Country-wise estimated age standardised incidence rates for leading cancer in females, 2020



Source: Globocan data, International Agency for Research on Cancer, 2022

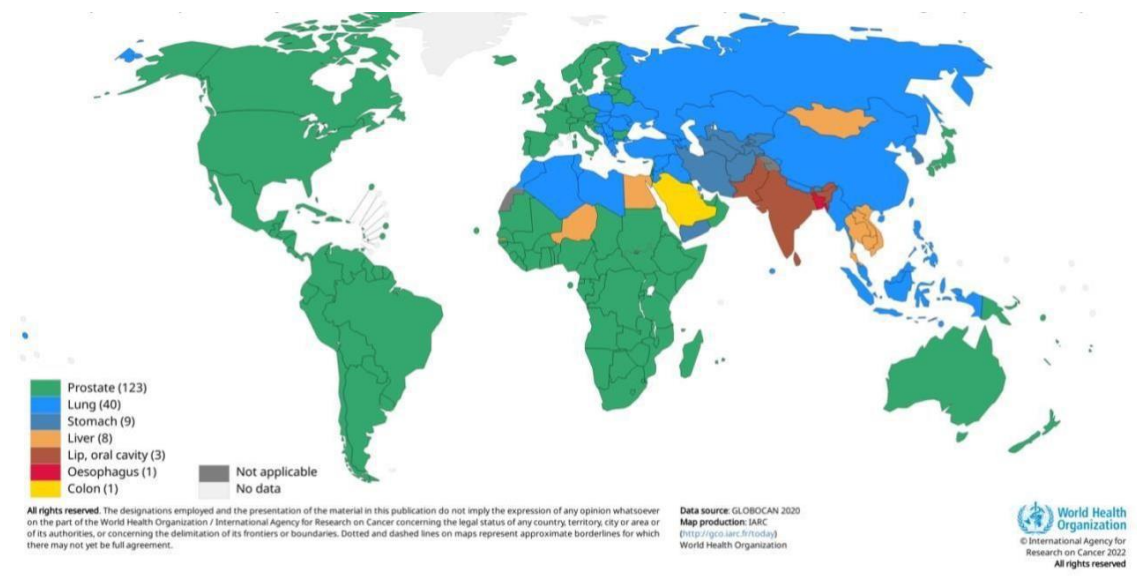
Figure 1b: Country-wise estimated age-standardised death rates for leading cancer in females, 2020



Source: Globocan data, International Agency for Research on Cancer, 2022

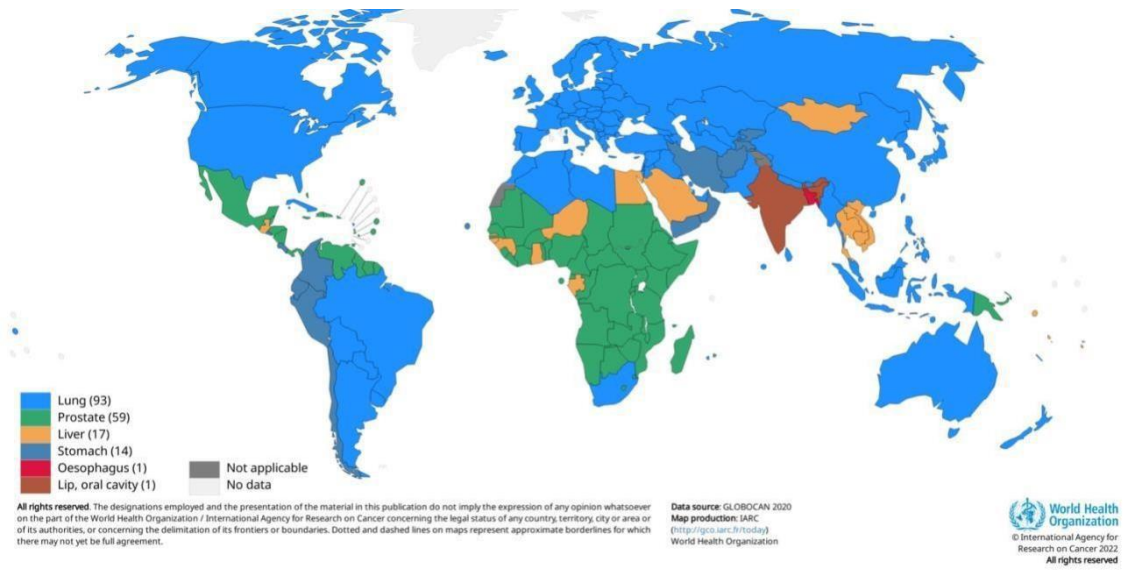
Appendix A.2: Country-wise estimated age standardised incidence and death rates, males

Country-wise estimated age standardised incidence rates for leading cancer in males, 2020



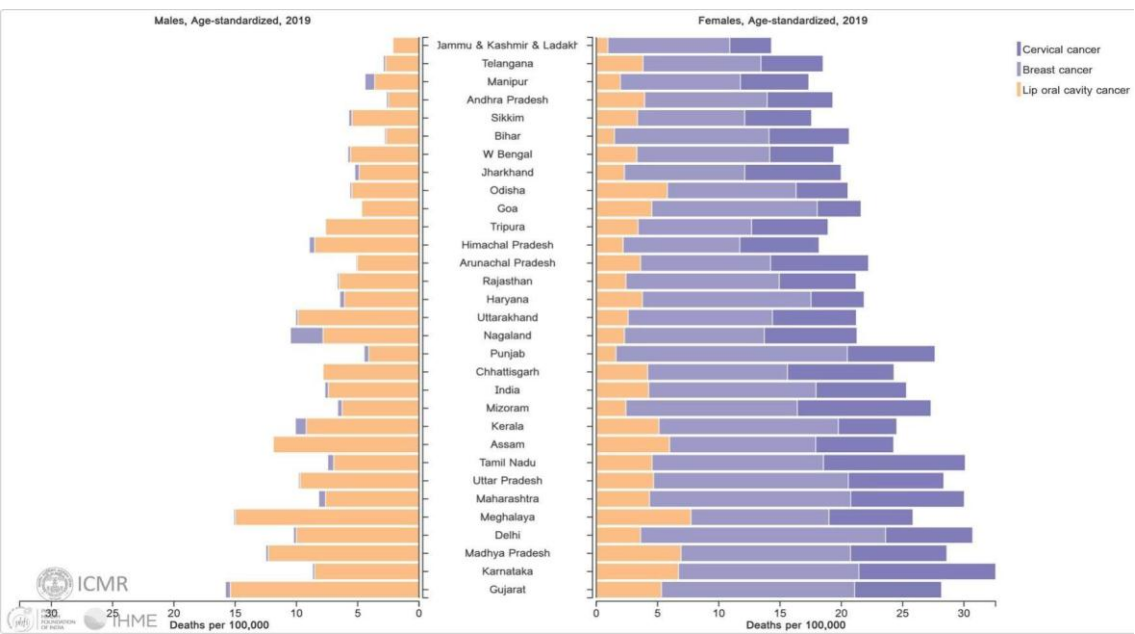
Source: Globocan data, International Agency for Research on Cancer, 2022

Country-wise estimated age-standardised death rates for leading cancer in males, 2020



Source: Globocan data, International Agency for Research on Cancer, 2022

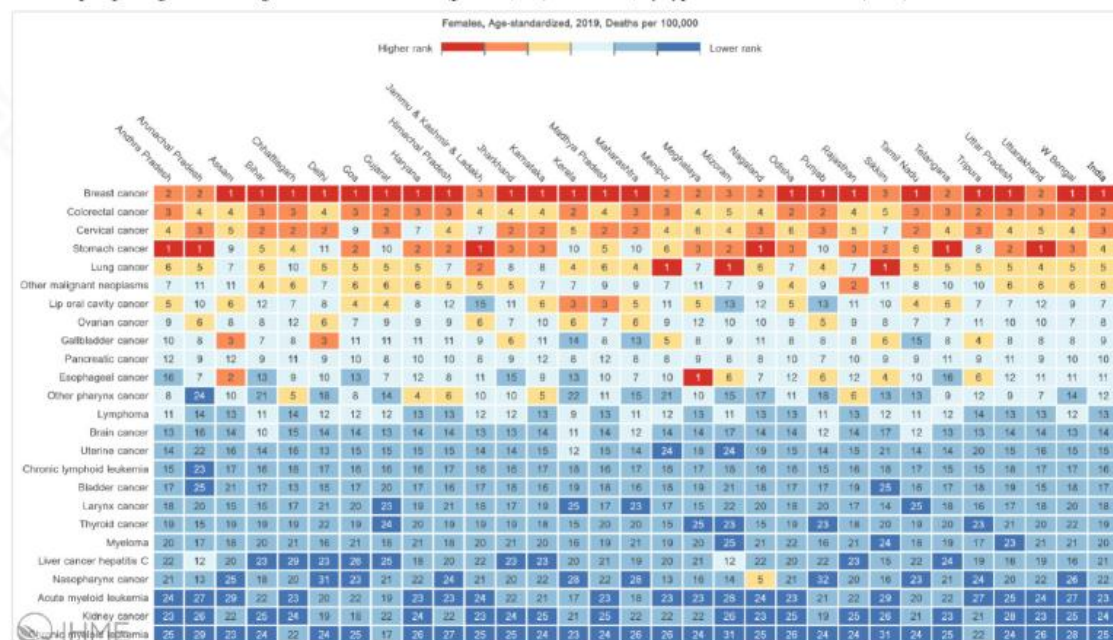
Appendix A.3: Age-standardised death rates (per 100,000) of cancer in India, 2019



Source: GBD Compare India, 2019, IHME

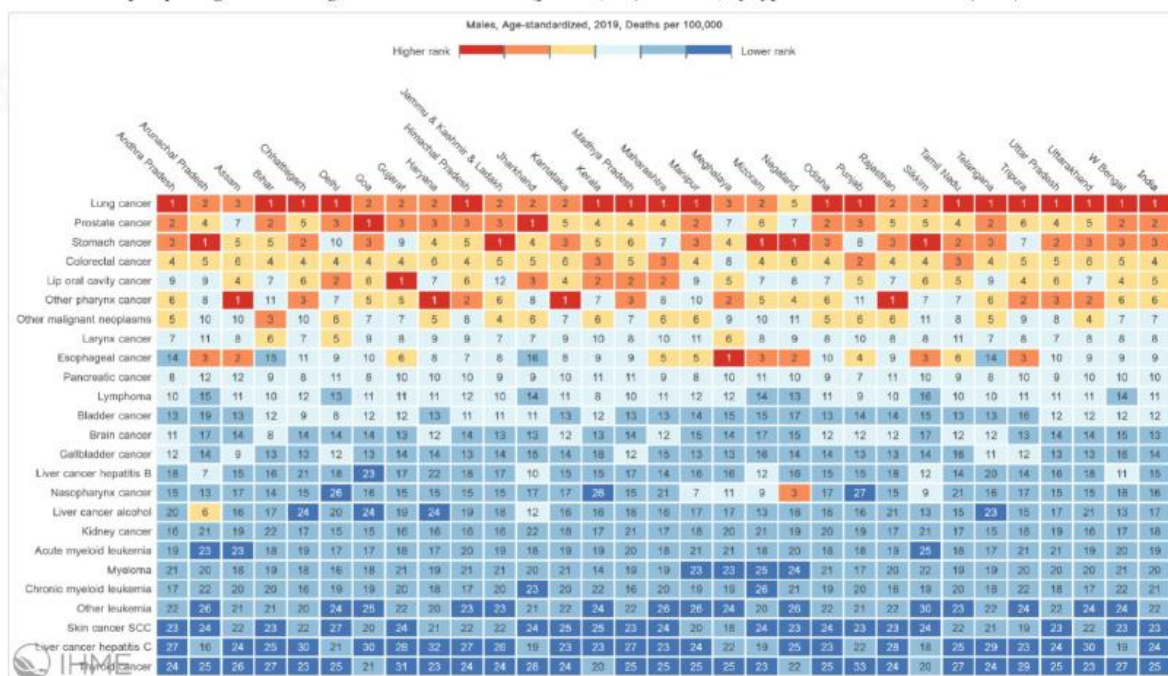
Appendix A.4: Heat maps depicting state-wise age-standardised deaths in India.

Heat map depicting state-wise age-standardised deaths (per 100,000) in females, by types of cancers in India (2019)



Source: GBD, 2019.

Heat map depicting state-wise age-standardised deaths (per 100,000) in males, by types of cancers in India (2019)



Source: GBD, 2019.

Adaptation and resilience for livestock sector in india: Need for innovation capacities within s & t policy development

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Abstract

This paper argues that in order to build resilience within the livestock sector in India, there is a need to inculcate innovation capacities in the ways in which science and policy interact with each other. The livestock sector needs to change the existing policy agenda of 'yield only' to accommodate environment and social equity components. Science should cater to policy needs but science needs to be open to different forms of knowledge without restricting to development of technologies to cater to policy agenda only. To build adaptive capacities within the livestock rearing communities (mainly small and marginal farmers) for a sustainable livelihood, innovation capacities which promotes the convergence of science along with different forms of knowledge and policy or norms for not only increasing production or yield but conservation of biodiversity and ecological systems is desirable.

1. Introduction

In the last decade, the Indian agricultural and allied sector has been stagnant, and, in the latter half, the annual growth rate has declined from 6.8 per cent in 2016-17 to 4.6 per cent in 2021-22. The long-term trend in the share of this sector in India's total GDP has been hovering around 18 per cent over the last decade. Despite the stagnation in this sector, the percentage of livestock increased from 4.0 per cent in 2011-12 to 6.2 per cent in 2020-21. This reflects the growing importance of livestock in Indian economy. Traditionally, the importance of

livestock in Indian households has been paramount. They have not only been a source of income but also an asset that serve as insurance and savings to deal with crises, especially for the marginal section of the rural population. The current concerns surrounding climate change and its impact on the agricultural sector raise some doubts.

Livestock has a dual relationship with the phenomenon of climate change. Livestock contributes to climate change by adding more greenhouse gas (GHG) emissions. Interestingly, the rising temperatures on account of this GHG-induced warming, in turn, potentially impacts the livestock, especially dairy cattle. Although the former has been discussed extensively in the mitigation strategy of climate change, the latter related to adaptation has not received much attention from social scientists and policymakers, although studied to a certain extent primarily by agricultural scientists.

According to FAO, the total emissions from global livestock production are around 7.1 gigatonnes CO₂ eq per annum for the 2005 reference period, with a share of about 15 per cent of the overall human-induced GHG emissions (Gerber et al. 2013, 15). Over the period 2005- 2015, the total emissions from the dairy sector increased by 18 per cent because of an increase in their population by 11 per cent, which also resulted in an overall increase in milk production by 30 per cent. The emission intensities, however, declined by 11 per cent over the same period (Food and Agriculture Organization of the United Nations (FAO) and Global Dairy Platform Inc. (GDP) 2019, 7). The mitigation measures aimed to reduce the emission intensity and, thereby, the absolute emissions have been partially successful because of the decline in the former. However, it is imperative to reduce total emissions as the world moves towards carbon neutrality by 2050.

Asia remains the world's largest milk producer contributing to more than 40.0 per cent of the global milk production in 2020. It showed a year-over-year growth rate of 2.6 per cent, with India, China, Pakistan, and Turkey contributing mainly to this growth. Due to a favourable monsoon and improved feed and fodder, milk production reached 195 million tonnes in 2020, an increase of 2.0 per cent compared to 2019 (FAO 2021). India is currently the world's largest milk producing country and contributes more than half of Asia's production and almost one-fifth of the global output. However, this sector is particularly vulnerable to the threats of climate change, and the risks associated with it can severely impact production as temperatures rise and humidity level increases (Press Trust of India (PTI), 2017). Hence, adaptation to the changing climate¹ would be crucial to ensure that the dairy sector continues to play a prominent role in India's agricultural and food sectors. However, as noted in the recent IPCC AR6 WGII Summary for Policymakers (IPCC 2022, 8), to ensure the proper implementation of these adaptability measures, it is essential to recognise the changing climate scenario, the need for adaptability and the importance of policies, both scientific as well as social: "The recognition

of climate risks can strengthen adaptation and mitigation actions and transitions that reduce risks. Taking action is enabled by governance, finance, knowledge and capacity building, technology and catalysing conditions. Transformation entails system transitions strengthening the resilience of ecosystems and society.”

The following section discusses the evidence that climate change negatively impacts livestock productivity, mainly relying on the scientific literature. We discuss both direct and indirect effects on livestock productivity, especially that of the bovines and the methodology of the study (section 2). The third section analyses how climate change and adaptation policies have directly or indirectly influenced the livestock holding pattern in India, focusing on coastal India. We focus on coastal India as this region is highly vulnerable to climate change. The section presents statistical evidence based on the Livestock Census data of India and the changes in livestock holding in the coastal regions of India (section 3). The holding patterns of livestock from the recent 77th round of the NSSO survey based on the landholding size of the households is presented in section 4. The section argues that the livelihoods of the landless and marginalised operational land-holding households would be most impacted due to their lack of access to resources, both economic and financial. The fifth section discusses the importance of science and technology policies for implementing adaptability measures to protect the livestock and the livelihoods of these marginalised sections. To elaborate the same, a specific study of Gujarat state is conducted to analyse the S&T policies and development of livestock in the state. The sixth section concludes the paper and stresses the need for innovation capacities so that regional policies and being focused for climate resilient livestock development.

2. Livestock and climate change

The mitigation strategies of greenhouse gas emissions have drawn substantial attention since the Working Group III of the Fourth Assessment IPCC Report of 2007, to livestock as a source of emissions (IPCC 2007, 66). The emissions happen directly through the raising of animals, in the form of methane from enteric fermenting and nitrous oxide from manure storage and carbon emissions from the consumption of feed and energy needed for the rearing of the livestock. On the other hand, there are indirect emissions also from livestock rearing. Although some recent progress has been made to reduce the emissions intensity from the livestock, to increase the effectiveness of this strategy it is also imperative to consider the complex interactions occurring among the various components of the livestock production system (Grossi et al. 2019, 74).

Even in the case of effective adaptability measures, it is essential to understand how climate change impacts livestock, both directly and indirectly. The direct impact is on animal physiology, production, and behaviour (Henry, Eckard,

and Beauchemin 2018, s447; Henry et al. 2012). The heat stress in livestock caused by rising temperatures and warm and humid conditions reduces feed intake, increases water intake and alters physiological behaviours (Nardone et al. 2010). The scientific explanation behind this phenomenon is that animals have a thermal comfort zone, and within that optimum range of temperature and humidity, their physiological activities properly function (Rojas-Downing et al. 2017, 148). It impacts their normal physiological activities outside that zone, leading to adverse health conditions, increased mortality, and declining populations because of poor reproductive health. The changing climatic scenario also has indirect impacts on the livestock through poor quality forage because of impacted pastureland, shortage of feed and fodder, lack of water resources, loss of biodiversity needed for their sustainability, and increasing incidences of parasitic and vector-borne diseases (IPCC 2022, SPM-10; Cheng, McCarl, and Fei 2022).

The lack of regular physiological activity impairs livestock productivity in meat and dairy production. In particular, dairy cattle are highly susceptible to heat stress due to their relatively higher metabolic rate during lactation. It is most negatively impacted in a high- temperature zone, especially in the exotic breed cattle (Das et al. 2016). When the temperature-humidity index exceeds 70, there is a negative relationship between dry-matter- intake (DMI) and milk yield. Both decline at 0.23 and 0.26 kg per day with every unit increase in the Temperature Humidity Index (THI) beyond 70 (Johnson et al. 1962). A recent study found that exposing dairy cows to moderate heat stress over four days in a climate chamber-controlled study reduced milk yield by 53% and reduced dry matter intake by 48% (n = 6) (Gantner et al. 2017). With the increasing yield of milk production over the years, dairy cattle have become more sensitive to such temperature changes, which eventually affect production (Berman and Kofinas 2004; Food and Agriculture Organisation of the United Nations (FAO) and Global Dairy Platform Inc. (GDP) 2019, 16).

This reduction in milk and meat production yield becomes concerning, particularly for low- income countries like India, for three reasons. Firstly, given the projections of global population growth, a major section of the population in the tropical and subtropical regions are dependent on these sources of animal protein as a significant source of nutrition (De Almeida 2018, 1178). Secondly, the impact of this heat stress from climate change would be felt more in the tropical countries because of the already existing high temperatures in this region, lack of economic resources and the agrarian production system (Banik, Pankaj, and Naskar 2015, 178). Thirdly, 58 per cent of Indian households are currently engaged in animal farming, and 71 per cent own some form of livestock (except pets). Among the rural households, 48.5 per cent owned cattle (16.4 per cent in milk, 19.6 per cent in young stock, 12.5 per cent in others), 27.8 per cent in buffalo (10.7 per cent in milk, 11.7 per cent in young stock, 5.4 per cent in others), 21.9 per cent in ovine and other

mammals, and 10.9 per cent in poultries (Ministry of Statistics and Programme Implementation 2021, 66). So, any impact on the milk yield and meat production would severely impact their livelihood during a phase when the agrarian economy in India is already reeling under a severe economic crisis. This would force the Indian farmers to adapt to the changing climatic conditions, which might become particularly challenging due to insufficient resources.

Interestingly, micro-level studies have shown that adaptive practices such as shelter modifications, water cooling or sprinkler systems and strategic nutritional supplements have evolved in coastal India due to climatic conditions (Maiti et al. 2014, 57). Another pattern that is also observed is the changing composition in the livestock holding in favour of small ruminants like goats and sheep. Sheep and goats generally appear less susceptible to heat stress. Goats are much better adapted to desert, tropical and subtropical environments (Silanikove and Koluman (Darcan) 2015, 32). These ruminants' ability to tolerate extremes of temperature and humidity and to function well even in water deprivation, water restriction and energy restriction is well documented in the literature (Kaliber, Koluman, and N 2016; Berihulay et al. 2019, 2). Although more research is needed in this field, there are some studies which suggest that the goat's voluntary feed intake declines when the ambient temperature is more than 10°C above their thermal comfort zones and the quality of milk also gets impacted (Lu 1989). Therefore, given the higher ability to tolerate extreme temperatures and humidity, there is a possibility that there would be a shift towards favouring the holding of small ruminants like goats and sheep rather than beef and dairy cattle.

There is some evidence from livestock holding patterns that such changes might already occur in other parts of the globe. It is observed in South America that under a hot and dry scenario, the numbers of beef and dairy cattle are projected to decrease by 3.2% and 2.3%, respectively, while sheep numbers increase by 7% (Seo, McCarl, and Mendelsohn 2010, 2492). Another study, using data from 9000 African livestock farmers in 10 African countries, found that in warmer locations, producers favoured goats and sheep rather than beef cattle (Seo and Mendelsohn 2008, 156). Since goats have numerous advantages that enable them to maintain their production under extreme climatic conditions, goats may play an essential role in adapting to harsh conditions due to climate change (Darcan and Silanikove 2018, 35). It would be interesting to see whether a similar pattern over the years is also observed in the case of Indian agriculture, wherein the process of adaptability, Indian farmers, especially in the coastal belts, are shifting towards holding more small ruminants. The livestock development policies in India over the years have favoured bovines, especially cattle in terms of research allocation as well as funding. Therefore, it is essential to evaluate how prepared are we in terms of scientific research and policies to adapt to climate change?

2.1. Methodology: Data collection for this study was based on secondary and primary sources. An archival research and data collection from key documents and Annual Reports of several administrative departments, developmental programmes were carried out. Livestock census and National Sample Survey Office (NSSO) data was collected and processed. A thorough literature review was carried to tap the science and policy pertaining to livestock sector. The literature review and the preliminary study of the livestock sector in India, point to the ‘agenda-setting theory of change’ put forward by John W. Kingdon in 1984, which may explain the knowledge policy convergence within the sector.

3. Livestock holding in india

Here, in this section, we report the livestock population for all of India, especially the coastal states, to capture whether any change in the pattern of livestock holding is exhibited. Table 1 shows the change in livestock population in India based on the Livestock Census data. Although there has been a decline in the cattle population since 2007, there has been an increase in the buffalo population over the last decade. Hence, there was a marginal decline in the overall bovine population between 2007 and 2019. There is a substantial increase in small ruminants (such as sheep, goat) population by 6.0 and 3.8 per cent, respectively, over the same period. Although there is no strong evidence of a changing pattern in the livestock holding at an all-India level, the pattern is quite evident when we take a closer look at the coastal states in India.

Table 1: Livestock population in india

Year	2007	2012	2019	Change in % (2007-2019)
Livestock	(numbers in millions)			
Cattle	199.1	190.9	193.5	-2.8
Buffalo	105.3	108.7	109.9	4.3
Bovine (Cattle+Buffalo)	304.4	299.6	303.3	-0.4
Sheep	71.6	65.0	74.3	3.8
Goats	140.0	135.2	148.9	6.0
<i>Source: 19th and 20th Livestock Census, Department of Animal Husbandry, Dairying and Fisheries, Government of India.</i>				

The specific reason to focus on coastal India is that the Indian coastline is one of the most vulnerable region to climate change impacts, including extreme temperatures, changes in precipitation patterns, increased incidence of extreme weather events and sea-level rise. Hence, given the extreme conditions, it is more likely that the changing pattern is evident in the coastal belt than in the inner heartland of India. To study the coastal belts, we focus on ten states along the coastline — Andhra Pradesh, Telangana, Gujarat, Goa, Kerala, Karnataka, Maharashtra, Tamil Nadu, Orissa and West Bengal. Table 2 shows the share of livestock population in these ten coastline states of India from 2007 to 2019. Although the share of the total livestock population in coastal India has

declined only marginally by around 1.8 per cent from 2007 to 2019, there is a drastic decline in the bovine population by almost 10 per cent. Among the small ruminants, the share of the sheep population has increased by 7.6 per cent, while the population of goats has marginally declined by 1.2 per cent.

Table 2: Share of coastal india in india's livestock population

Year	2007	2012	2019	Change (2007-2019)
Livestock	(in per cent)			
Cattle	45.4	43.4	41.8	-3.6
Buffalo	34.7	29.7	28.5	-6.2
Bovine Cattle+Buffalo)	80.1	73.2	70.3	-9.8
Sheep	71.8	73.3	79.4	7.6
Goats	45.6	40.5	44.4	-1.2
Total livestock (including pigs)	46.3	43.0	44.5	-1.8

Source: 19th and 20th Livestock Census, Department of Animal Husbandry, Dairying and Fisheries, Government of India.

As shown in Table 3, the shift in the pattern of livestock holding towards smaller ruminants becomes more evident in coastal India if one closely focuses on the absolute numbers and their change over the period 2012-2019. We find that over this period, when the impacts of climate change became more prominent, the bovine population of coastal India declined by almost 2.7 per cent while the sheep and goat population increased by almost 22.1 per cent – a shift in the pattern of livestock holding in coastal belts. So, a trend is developing in India where one can see that there is a change in the holding pattern of livestock. However, the issue assumes greater significance in the context of who will be more well-equipped to adapt to these changing patterns of livestock holding. More importantly, which class of farmers would be able to adapt to the changing climatic conditions and sustain in case they decide to persist in holding onto their existing bovine population? This also assumes greater significance in light of the maladaptation policies highlighted in the WGII AR6 IPCC report.

Table 3: Livestock population in coastal india

Year	2012	2019	Change in % (2012-2019)
Livestock	(numbers in millions)		
Cattle	82.9	80.8	-2.5
Buffalo	32.3	31.3	-3.1
Bovine (Cattle+Buffalo)	115.2	112.1	-2.7
Sheep	47.7	58.9	23.5
Goats	54.6	66.0	20.7
Sheep and Goats	102.3	124.9	22.1

Source: 19th and 20th Livestock Census, Department of Animal Husbandry, Dairying and Fisheries, Government of India.

4. Adaptability Policies: Who is well equipped to adapt?

There have been a few recommendations for the adaptability of livestock to the changing climatic conditions, which are mainly applicable in the western world. However, many of these recommendations are quite capital intensive, beyond the capacity of the small farmers in India, who are already resource-constrained (Mahajan et al. 2015, 294). Hence, given the practical applicability of these policies, adaptation policies must be localised and consider the socio-economic conditions of the domestic economy. It is, therefore, crucial to determine the pattern of livestock holding depending on their financial and economic capacity – a proxy of which can be the size of their operational holding – to understand better which farmer's groups, based on their economic conditions, are well equipped to adapt to these changing conditions.

We consider the livestock holding by type of landholding category (Table 4). Here, landless households are those which have a holding of 0.002 hectares or less; households with 'marginal' holding include those who have more than 0.002 hectares but less than or equal to 1 hectare of land; and households with more than 1 hectare but less than or equal to 2 hectares are 'smallholders'. 'Semi-medium' landholding households have more than 2 hectares but less than or equal to 4 hectares; 'medium' holding refers to more than 4 hectares but less than or equal to 10 hectares; and households with more than 10 hectares of land are 'large' landowners.

Table 4: Average number of livestock owned per 1000 households in each landholding category, 2019

Landholding	Cattle	Buffalo	Ovine	Poultry
Landless	878	333	819	1762
Marginal	1164	520	992	1267
Small	1376	878	770	1453
Semi-medium	1700	1162	1054	1405
Medium	2348	1563	1770	619
Large	2768	2307	1584	1354
<i>Source: Calculated using NSS Land and Livestock Survey 2019</i>				
<i>Note: NSS 77th round does not separately report individual smaller livestock like goat, sheep, etc. but report it collectively as Ovine and other mammals.</i>				

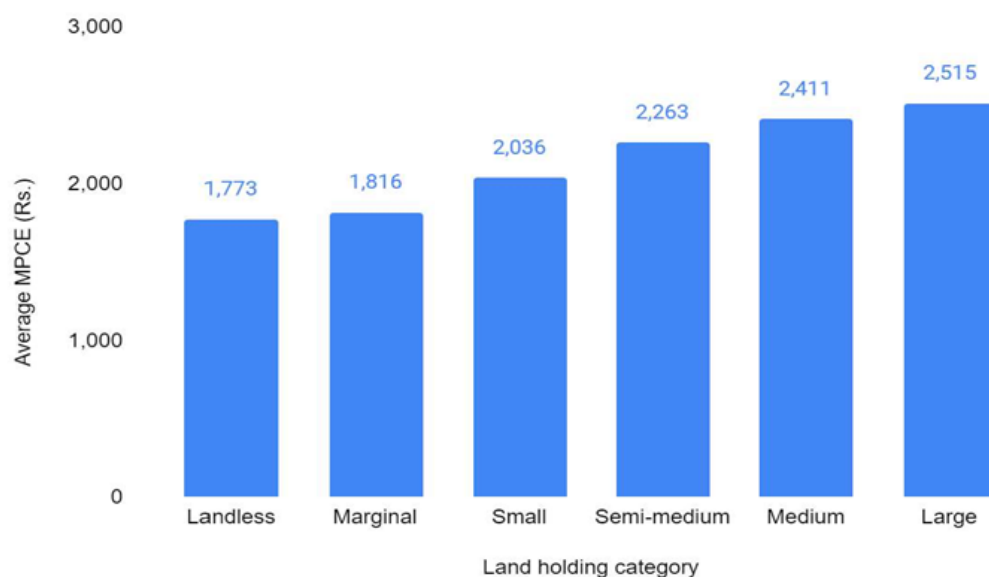
On average, households with larger landholdings own more bovine livestock. On the other hand, landless households own more poultry on average as compared to any other landholding category. For such households, owning poultry may be a source of sustenance as well as additional earnings. This may be particularly true during times of economic distress, such as during and after the slowdown of the Indian economy after 2018, as well as the pandemic and lockdown.

At the same time, large landholders owned a high number of poultry in 2019, comparable to the average numbers owned by small and semi-medium landholding households. Unlike in the case of landless households, the rationale in the case of large landowners may be to increase income in shorter timespan. On average, medium landowners, followed by the large and semi-medium, owned the highest numbers of ovine animals that are also more climate-resistant (Table 4). However, these medium and large landowners only constitute 1.4 and 0.1 per cent of rural households, respectively, while marginal landowners constitute more than 76 per cent (Table 5). Among the marginal and landless households (constituting almost 85 per cent of rural households), bovines make up a chunk of their total livestock holding.

Table 5: Composition of rural households, 2019

Landholding	Percent
Landless	8.2
Marginal	76.5
Small	9.3
Semi-medium	4.4
Medium	1.4
Large	0.1
<i>Source: Authors' calculations using NSS Land and Livestock Survey 2019.</i>	

Figure 1: Average monthly per capita consumer expenditure (Rs.), 2019



Source: Calculated using NSS Land and Livestock Survey 2019

It could be the case that those households who do not own land may be engaged in other activities such as salaried or wage employment which also does not require owned land. We, therefore, consider the average monthly per capita consumer expenditure (MPCE) by category (Figure 1). This shows a clear pattern of rising MPCE by land ownership and therefore indicates their differential financial capacities to adapt to climate change. Large and medium landowners indeed appear to be better placed to use more resources and make changes in their livestock ownership or other activities in order to adapt to climate change. Such resources may be hard for those who do not own any land or own tiny plots of land and are reliant on agriculture and agriculture-based activities. For these groups of farmers, whose livelihood still depends on the livestock but has limited resources, there is a need for policies to support to ensure adaptability and resilience among the farming community. There is also a need for apt scientific policies based on regional needs and domestic constraints to help them adapt. The following section analyses the S&T policies for livestock development using the case of Gujarat State in India. Gujarat has been the seat for dairy development in India. The section analyses two livestock development programs, their S&T components along with expenditure of the state to understand the S&T policies landscape in the state.

5. S&T policy for Livestock development using the example of Gujarat state.

Animal Husbandry has been a state subject wherein the state government designs the policies and programmes suitable for livestock; however, the structure of livestock sector was characterized by centralization, where central Government and its leadership are important in defining the direction of the sector (Misra and Pica-Ciamarra, 2010). The plans and policies for livestock sector are ascertained by the Union government, while its implementation is left to the discretion of the states. So, the state policies and programmes are often guided by the larger national objective. The Department of Animal Husbandry and Dairying (DAHD) under the Ministry of Agriculture and Farmers Welfare of the Government of India lay guidelines for the state governments to formulate policies and programmes pertaining to livestock.

Gujarat has a unique geographical terrain with coastline, grasslands, wetlands and saline desert of Rann. According to surveys and collection by Zoological Survey of India, Gujarat exhibits 101 species and subspecies of mammalian fauna belonging to 68 genera, 33 families and 12 orders with sexual and intra-specific variation in different species (Alfred, 2000). The state also has a diverse livestock population with intra-specific variations. Each state with its regional dynamics creates a sectoral push which drives the sector in the state. For example, the successes of Anand Milk Union Limited (AMUL) in Gujarat illustrate the regional dynamics which shaped the milk cooperatives and in turn the livestock sector of the state. How responsive have the states been in dealing with regional dynamics for development of a sector? If we consider the case of cattle breeding within livestock (which has been one of the most sought

S&T policy area since independence), we find that the guidelines adopted in Gujarat for cattle breeding i.e. Bovine Breeding Policy, 2013, did not take into cognizance the dynamics within the state, it rather adhered to the guidelines set by the Union government. In this backdrop we analyse how S&T policy landscape in Gujarat and India as a whole unfolded by analyzing two major livestock development programmes and their science and technology (S&T) components.

Livestock research in India was mainly centered around big ruminants with major focus on cattle and improving their productivity, followed by buffalo, goat, poultry and sheep (Birthal, 2002). As a result, the research prioritisation, technology development, institutional incentives and budget allocation were biased towards cattle and dairy subsector with top down institutional mandates and preconceived goal of increasing milk production (Misra and Pica-Ciamarra, 2010). The programmes studied are, a) Intensive Cattle Development Project (1965) - a national programme being implemented by the state and b) Operation Flood (1970) - a programme being implemented based on the success story of Kaira District Cooperative Milk Producers Union Limited, which led to a big push to the dairy sector to replace the existing practices with entirely different technology and organization.

In the immediate post-independence period, the measures for livestock improvement in the country started with the Key Village Scheme (KVS), a scheme of the Union government. KVS initiated in 1951 was the first organized effort for cattle improvement introduced in rural areas across 600 centres and each centre catered to three or four villages (GOI, 1952). It focused on multiplication of superior germplasms (mainly proven indigenous germplasm) from established farms to other breeding tracts of the country with provisioning of improved feed, disease control, scientific management practices and organized marketing practices (GOI, 1952). Under the scheme, elite proven bulls were distributed by the Union government to the states to develop well defined breeds for milch and draught purposes. The implementation of the scheme was brought about by dividing the states into zones according to the available breed, to bring about improvement in the cattle population. Gujarat had two notable breeds of cattle, Kankrej and Gir, both of which were used extensively for draught purposes and milk production. The Gujarat Animal Husbandry Department divided the state into three cattle breeding zones- a) Gir breed zone - selective breeding with Gir; b) Kankrej breed zone - selective breeding with Kankrej; and c) Non-descript or mixed zone - grading up of the non-descript with Gir and Kankrej (GOI, 1962). These breeding guidelines were adopted based on the guidelines set by Indian Council of Agricultural Research (ICAR) in 1950 which stated that 'milking capacity of well-defined milch breeds should be developed to the maximum by selective breeding and their male progeny should be used for the development of the non-descript cattle; and selective breeding for well-defined draught breeds for milk should

not impair their quality for work' (GOI, 1962). However, this breeding objective in Gujarat changed during the seventies with the implementation of Operation Flood (OF) in 1970. OF placed greater emphasis on crossbreeding of indigenous cattle with high yielding exotic breeds (George, 1985) which influenced the shift in breeding emphasis in Gujarat from elite indigenous breeds to exotic high yielding breeds, in order to improve the cattle stock and increase their milk production. This shift also corroborated with the guidelines adopted by the centre based on the recommendation of 'National Commission on Agriculture', 1976. Gujarat followed intensive crossbreeding with the implementation of Intensive Crossbreeding Programme across four districts (Vadodara, Valsad, Rajkot and Mehsana) in 1983 (GOG, 1991). A total of 50 crossbreeding centres were set up in these districts which covered 247 villages by the year 1990-91 and catered to about 77000 breedable cattle with services like AI, preventive inoculation, castration and general treatment to intensify crossbreeding.

However, until 2013 there was no breeding policy in Gujarat to specify the approach of breeding, the choice of exotic breed to be used or the level of exotic inheritance to be maintained. In 2013, Gujarat Animal Husbandry Department formulated a Bovine Breeding policy to promote breeding and development of cattle and buffalo in the state (GOG, 2013). In the absence of 'a policy' (which does come to exist in 2013), the state's breeding policy was taken as evident in the livestock or animal husbandry schemes/programmes.

5.1. Livestock development programmes and their S&T components

i) Intensive cattle development project (ICDP)

ICDP was initiated in 1965 to stimulate the KVS and provide the cattle owners a package of practices via ICDP centres located in selected areas (breeding tracts of indigenous breeds and in the milksheds areas) to bring about marked improvement in milk production. The programme included provisioning of semen doses of exotic germplasm through Artificial Insemination (AI), more feed and fodder production, disease control and coverage for all-round cattle development to increase the production of milk in the country (GOI, 1972). Within a year of its implementation, 21 ICDPs were initiated throughout the country mainly in those districts that had greater potential for cattle development and it was expected that improved breeds and scientific methods of breeding (as propagated through ICDP) would diffuse from these districts to the neighbouring districts. In Gujarat, the programme was implemented in 1965-1966 with an objective to double the per head milk production of cow by 2014-2015 (GOG, 2016). It took off only in the Ahmedabad district in 1965 and later spread to other districts in the following years (Table 6).

Table 6: Coverage of ICDP in Gujarat

Districts	Year of establishment	ICDP centres			
		1990-91	2000-01	2010-11	2021-22
Ahmedabad	1965	100	74	101	44
Vadodara	1970	84	114	106	69
Surat	1969	100	80	80	71
Mehsana	1970	100	113	75	75
Rajkot	1969	70	93	92	68
Bhavnagar	1995	-	65	61	29
Junagadh	1995	-	66	66	66
Valsad	1996	-	64	60	18
Sabarkantha	1996	-	76	76	53
Banaskantha	1997	-	50	50	50
Panchmahal	2008	-	-	20	20
Patan	2008	-	-	50	50
Kachchh	2010-12	-	-	50	50
Barunch	2010-12	-	-	50	78
Amreli	2010-11	-	-	34	59
Anand	2011-12	-	-	-	19
Gandhinagar	2011-12	-	-	-	77
Kheda	2011-12	-	-	-	25
Tapi	2011-12	-	-	-	29
Dahod	2012-13	-	-	-	20
Jamnagar	2012-13	-	-	-	20
Narmada	2012-13	-	-	-	27
Surendra Nagar	2012-13	-	-	-	43
Aravalli	2016-17	-	-	-	29
Botad	2016-17	-	-	-	18
Navsari	2016-17	-	-	-	47
Total	-	-	-	-	1154

Source: Compiled from Bulletin of Animal Husbandry and Dairying Statistics (various years), Directorate of Animal Husbandry, Government of Gujarat, Gandhinagar.

ICDP centres were set up to cater the breedable cattle population of the villages. It offered services like male castration, AI, preventive inoculation, treatment for sterility cases and general treatment for diseases. By 2021-22, the project extended to 26 districts (ICDP blocks) with the coverage and spread

of ICDP across the districts of Gujarat (as per their year of implementation) has been presented in Table 7. Further, the services rendered under ICDP have also been described (Table 7). The various components of the project were grouped under S&T components and other knowledge components.

Table7: ICDP Components and Achievements (in nos.) towards Cattle Development in Gujarat

	1990-91	2000-01	2010-11	2021-22
Total Districts Covered	5	10	15	26
No. of Centres	454	795	971	1154
No of Villages covered	1726	3235	4187	4887
ICDP-S&T components				
Male Castration	34106	66574	66902	40471
Artificial Insemination	297098	474679	762853	1381320
Natural Service	141197	-	-	
Preventive Innoculation	2053151	8420640	6366894	2949992
Sterility treatment	68435	188628	259179	148696
General Treatment	868242	261555	284844	533117
ICDP- other components				NA
Milk Yield competition	442	510	662	
Calf subsidy	239	-	-	
Cattle show	189	-	-	
ICDP - Fodder Production and Improvement				NA
Fodder demonstration plots	2646	-	-	
Improved Fodder seeds distribution (kg)	255181	904588	126295	
Silo pit subsidy	46	72	16	
Chaff cutter subsidy	509	-	-	
Minikits distribution	-	15173	28930	
Source: Compiled from Bulletin of Animal Husbandry and Dairying Statistics (various years), Directorate of Animal Husbandry, Government of Gujarat, Gandhinagar.				

S&T components: ICDP facilitated AI services, castrating useless bulls and providing health services for treatment of diseases and sterility. AI was a crucial component in the project which enabled faster delivery of improved germplasm (focus was on exotic breeds). The provision of natural services for insemination was also present, however much emphasis was laid on AI because of the convenience to inseminate large number of breedable cattle with limited elite bulls. Lack of elite breeding bull was one the major problem identified for cattle improvement in the country (GOI, 1952). ICDP provided a wide range of coverage in terms of AI facilities to different districts.

Other knowledge components: ICDP promoted milk yield competition with prizes and cattle shows in the villages to incentivize cattle owners to keep high yielding cow. Fodder component was also promoted under ICDP in terms of fodder demonstration plots, distributing improved fodder seeds and root slips of fodder, providing subsidies for chaff cutter, urea treatment, silopits, cattle sheds etc. (GOG, 1991). The fodder raised in Gujarat state include lucerne, jowar, bajra, maize, oat, guwar, mug etc. and the fodder seeds of these varieties were produced and multiplied at fodder farms attached to the cattle breeding farms of the state (GOG, 1997). Under ICDP, improved fodder seeds were distributed, the use of chaff cutters were popularized by subsidizing it and needy farmers were distributed fodder minikits free of cost. Though the project facilitated fodder development in the state, increasing milk production received greater priority than fodder production. In the initial years of implementation of ICDP, feeding and fodder development were assigned top priority but gradually yield aspect i.e., milk production seized the importance due to the crossbreeding initiative in the country.

ii) Operation flood (OF)

The success of cooperative structure of milk production and marketing in Gujarat (brought about by Kaira District Co-operative Milk Producers Union Ltd (KDCMPU)), made Gujarat the seat of Operation Flood programme. KDCMPU started to operate in Anand town of Kaira/Kheda district (now Anand district) based on the principle of shared means of production. Such co-operative system provided opportunities for constant learning, knowledge generation, technological and institutional changes within the system, which created the dynamics to generate adequate responses to the different requirements at different point of time (Raina and Sulaiman, 2007). This mechanism of collective ownership which bore the capacity to elevate income among the rural community drew attention of the policymakers. By 1960s, the example of KDCMPU supplying milk to Bombay urban markets made it understandable to the policy makers that the dairy development could be best attained by effectively linking rural milksheds with major urban markets (George, 1985). The success of AMUL, directive of the government to replicate KDCMPU (Amul or Anand pattern) to the other parts of the country, restructuring the dairying economy on the lines of advanced dairying country, supply of European dairy aid to India and cordial support from the Government of India enthused NDDB to hatch the plan for OF (Kurian, 2005). OF utilised the European dairy surpluses (milk powder and butter oil) to enhance the milk production and to establish a national dairy marketing grid to step up the domestic milk supply (George, 1985). NDDB along with Indian Dairy Cooperation (IDC)² were responsible for the operationalisation of OF in the country. It enabled commercialization of milk by improving the marketing chains and linking the milksheds with urban milk market in four metros by utilizing the funds generated from the dairy aid (Scholten, 1985).

The OF programme was conceptualized to replicate the AMUL model to different parts of the country. But it failed in doing so, because the state sponsored S&T based OF programme relied heavily on technological solutions rather than the basic tenets of AMUL model i.e. the ground level integration of the knowledge and policy, the practices of foraging, choice of fodder production in and around Kheda district, breeding practices or constant learning from the field. Since, KDCMPU enabled all round development of the cattle and buffalo like provisioning of feed and fodder, breeding services, veterinary care etc. to augment milk production and milk supply to the cooperatives, OF programme too stressed on similar services. It marketed technical inputs like AI services for improved breeding, compound cattle feed, veterinary services etc. along with setting up of rural milk producers' own cooperatives to increase the supply of milk to the cooperatives (Nair, 1985). But it failed to integrate the knowledge of the farmers or local communities and their learning mechanism in the day to day life in the formal S&T and policy structure. The first phase of OF in Gujarat was initiated in the districts around Kheda (Table 8) owing to abundance of milch stock in these districts and to enable flushing the cooperative with milk supply (George, 1985).

Table 8: Districts covered under operation flood (1970-80)

	Village cooperative Societies	Milk procurement by societies (lakh kg/day)	No of Societies providing AI services	Mobile vet clinics	Area under fodder crop (ha)
Banaskantha	790	1.24	96	17	-
Kheda	895	5.12	731	55	220
Mehsana	887	4.33	123	34	12
Sabarkantha	1064	2.12	136	13	-
Ahmedabad	161	0.28	-	-	-
Vadodara	660	0.91	162	10	-
<i>Source: Dairy India, 1983, Pp.32.</i>					

The various components (S&T and other knowledge components) involved in the project are evident from the table (Table 8). Components like fodder production, milk procurement and storage, health services and breeding services were emphasized in OF programme. But, fodder production was restricted only in Kheda and Mehsana districts in the first phase of while the main emphasis was laid on breeding and veterinary health care services. The programme sought to reform the existing milch stock consisting of cattle and buffalo with homogenized high yielding crossbred cattle via cooperatives (George, 1985). Underproductive indigenous cattle were crossbred with European breeds like Red Dane, Jersey, Holstein Friesian and Brown Swiss. In Kheda district where buffalos were the most predominant milch animals among the households, to increase the milk production during OF, germplasm

of European breeds were emphasized and propagated instead of buffalo breeds (George, 1985). This explains that the state dynamics had no role in shaping of a policy or programme. However, technology played an important role in the success of the programme. Since the objective of OF was to increase the supply of milk from rural milksheds to urban consumers, dairy technology played an important role in fulfilling the objective. Milk processing technology, milk pasteurization technology enabled processing of bulk milk procured from different milk collection centres and also to produce different value added products like butter, condensed milk etc.

5.2 Expenditure

To get a clear idea about the emphasis laid by the state and Union government on different components of livestock, a comparison of expenditure (revenue expenditure) on agriculture and allied services by the Union government and Gujarat state has been drawn (Table 9). From the table, a difference in priority in disbursing funds to different heads can be found. In Union government's expenditure list food storage and warehousing received the most funds while Gujarat on the other hand spend majorly on crop husbandry, co-operation, agricultural research and extension, forestry and wildlife, and animal husbandry. Dairy development receives minimum expenditure from the centre as well as from the state. However, expenditure for dairy development in Gujarat has increased from 0.15 per cent of the total agricultural expenditure in 2002-2003 to 1.89 per cent in 2012-2013, but dropped again in 2019-20. The share of expenditure for animal husbandry and forestry in Gujarat has dropped from 2002-03 to 2019-20 while the state has stepped up its expenditure for crop husbandry from 34 per cent in 2002-2003 to 43 per cent in 2019-20.

Table 9: Share of Revenue Expenditure on Agriculture and Allied Services of Union Government and Gujarat

	Union Government				Gujarat			
	1992-93	2002-03	2012-13	2019-20	1992-93	2002-03	2012-13	2019-20
Crop Husbandry	18.16	14	34.7	39.30	33.03	33.98	48.21	43.51
Soil and Water conservation	0.14	0.04	0.02	0.01	10.65	6.4	7.16	0.57
Animal Husbandry	0.39	0.3	0.32	0.60	11.41	12.13	8.96	8.66
Dairy Development	2.4	0.43	0.56	0.42	0.36	0.15	1.89	0.65
Fisheries	0.62	0.25	0.15	0.10	4.11	2.84	2.45	4.05
Forestry and Wildlife	1.31	1.08	0.48	0.42	17.67	19.54	8.84	9.46
Plantations	1.05	0.87	0.41	0.30	0	0	0	0.00
Food, storage and	45.88	78.34	56.52	48.57	2.78	1.86	1.77	0.86

	Union Government				Gujarat			
	1992-93	2002-03	2012-13	2019-20	1992-93	2002-03	2012-13	2019-20
Warehousing								
Agricultural Research and Education	5.73	4.19	2.93	3.18	12.44	16.11	14.11	11.65
Agricultural Financial Institutions	0.47	0.1	3.52	6.87	0	0	0	0.00
Cooperation	0.28	0.11	0.06	0.09	7.25	6.78	6.33	20.48
Other Agricultural Programme	23.56	0.28	0.33	0.13	0.29	0.2	0.29	0.10
Source: Estimated from combined Finance and Revenue Accounts of Union and State Governments in India, Volume I (various years), CAG of India; and All India Livestock Census (various years) Department of Animal Husbandry, Dairying and Fisheries, Government of India, New Delhi.								
Note- Capital expenditure is not included because the direct expenditure for different programmes is reflected by the revenue expenditure.								

Further, a detailed picture of the states expenditure (Plan) on animal husbandry has been presented in the following table (Table 10). The share of planned expenditure on animal husbandry shows cattle and buffalo development and veterinary services receiving the major share of the state's total spending, while feed and fodder development receive a miniscule amount (Table 10). The expenditure on cattle and buffalo has mostly remained the same over the years; while the share of expenditure on veterinary services has increased considerably from 1990-91 to 2021-22. Since, cattle and buffalo development received the most attention, detailed breakdown of it in 1990-1991 reveals, crossbreeding programme (Artificial Insemination scheme with semen bank and stud farms) and assistance to small farmers for crossbred heifers (drawing 41 per cent of the total state expenditure), followed by ICDP, supply of milch animals in tribal area, cattle breeding farms and subsidy to cattle breeding institutions and gaushalas (GOG, 1991). From this it can be inferred that within cattle and buffalo development, crossbreeding received the major share of funding.

Table10: Share of expenditure on animal husbandry by gujarat state (Plan)

	1990-91	2000-01	2010-11	2021-22
Cattle and Buffalo development	29.48%	26.22%	22.75%	30.70%
Feed and Fodder	3.95%	4.26%	2.93%	
Development				1.33%
Veterinary Services and Animal Health	27.43%	29.21%	39.03%	51.74%
Other expenditure*	39.15%	40.31%	35.29%	16.25%
<i>Source: Estimated from Bulletin of Animal Husbandry and Dairying Statistics (various years), Directorate of Animal Husbandry, Government of Gujarat, Gandhinagar.</i> <i>*Other expenditure includes animal disease extension and training, administrative investigation and statistics, poultry development, sheep and wool development, other livestock development, nucleus budget, extension and training</i>				

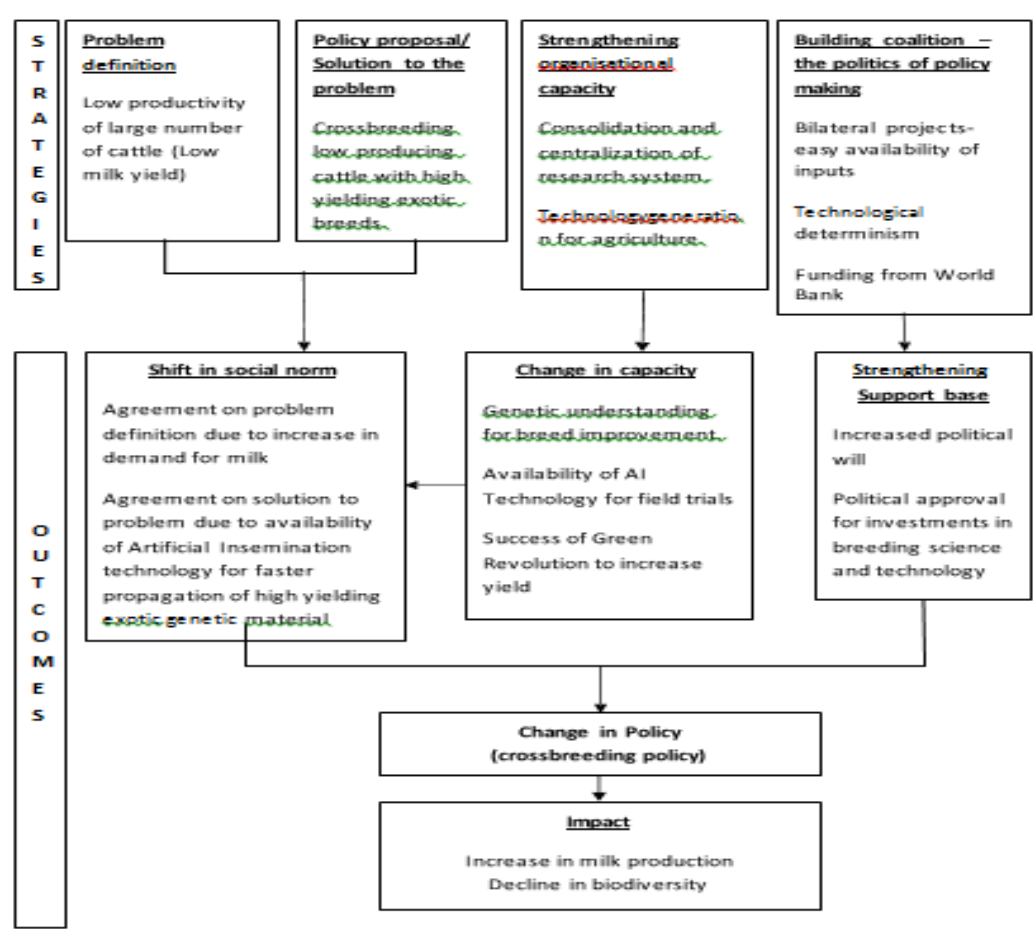
5.3. Analysis of livestock (Cattle) development policies and the s&t components

Though Animal Husbandry has been a state subject wherein the state Animal Husbandry Department designs the policies and programmes suitable to the requirements of the region, we confront massive centralization in the content of policies and programmes. Almost all the S&T components and the technology supply came from the centralized and consolidated research system which formed the main component of most of the major programmes for livestock development. State specific components were tailored by the centralized research system to feed into different components of the state. The focus of research and development for livestock development has been increasing milk yield. And one of the major reasons for achieving remarkable heights in milk production has been crossbreeding native cattle with high yielding exotic breeds. The crossbreeding policy was framed on the basis of some preconceived assumptions – i) high milk yield would meet the increasing demand, ii) easy availability of cattle genetic material from the bilateral projects initiated in the 1960s, and iii) the success of high yielding crop varieties introduced in the green revolution. The relationship between science and policy can be explained by the Agenda Setting framework.

The content of science and the scientific problem to be researched was framed according to the policies determined by an agenda of 'increasing milk yield'. The policy agenda for cross- breeding indigenous cattle with exotic cattle emerged in response to urban demand for milk. The problem of the low productivity of a large number of cattle converged well with the available technological solutions (like crossbreeding, artificial insemination) to improve their productivity, which elevated the idea of 'crossbreeding' over selective breeding or adequate feeding higher up to a policy agenda. Coalition building

with input (exotic germplasm) suppliers and funds from international agencies along with voices of qualified agricultural and veterinary scientists increased the political will which led to an opening of the policy window. Though other problems (besides yield per animal) were identified and researched by the sciences, it was breeding technologies that shaped the policy agenda. Scientific research hence played a subservient role in policy, feeding technologies and molecular genetic techniques to the policy goals and instruments for addressing one particular policy agenda of increasing milk yield. The following figure (Figure 2) explains the agenda setting in livestock research and development which favoured cattle breeding to enhance milk production.

Figure 2: Agenda setting policy change for cattle breeding during mid 1960s



6. The need for Innovation capacities to develop regional policies for climate-resilient livestock development

From the previous sections we find that the policies in India related to livestock development have mainly focused on large livestock with an exclusive focus on dairy cattle to increase yield per animal. These have been successfully delivered, and milk production has increased, but the livestock development policies largely ignored the climatic specificities, region specificities, nutrition

availability, or nomadic and pastoral communities in the different agro-ecological zones (George, 1985). This is because the institutions that formulate policies for the different domains of the livestock sub-sector are mostly inclined towards developing solutions for a common objective of high yield, and objectives like adaptability in response to climate change, biodiversity conservation, assured income source, loss of grazing common land and loss of pastoral livelihood got blurred.

Livestock research that gained momentum was crossbreeding native cattle with exotic high-yielding ones to increase productivity. Since then, S&T interventions for livestock development have mainly focused on livestock breeding. Of late, there has been ongoing research that focuses on reducing emissions from the dairy sector by tracking the carbon footprint of the dairy supply chain, measuring methane emission using the Sulphur Hexafluoride (SF₆) Tracer Technique, and also nutrient optimisation for reducing enteric methane emission. On the other hand, there is evidence of how climate change impacts the milk yield and the health of dairy cows, especially the exotic varieties and crossbreeds. However, hardly any dairy development policies or plans have been implemented to address these impacts because, till today, climate change concerns are yet to be integrated into the sectoral plans and programmes.

Under the National Innovations in Climate Resilient Agriculture (NICRA) project of the Indian Council of Agricultural Research (launched in 2011), heat stress and fodder scarcity have been identified as the major climate-sensitive issues affecting dairy farming in India. For a livestock production system to be sustainable in the changing climate scenarios, there is a need to identify the best adaptive breeds in different agro-ecological zones, especially given the warning from the recent IPCC report on maladaptation practices. Years of selective breeding, the seasonal movement of pastoralists with their stock, and grazing methods across the diverse agro-ecological landscape led to the development of several indigenous breeds with unique adaptive traits in India (Voelcker, 1893; George, 1985). They can walk long distances, ingest and digest low-quality feed (high cellulose content), survive on minimum feed during drought conditions, thermoregulation, resistance against diseases, high fertility, etc., compared to the exotic temperate breeds or the crossbreeds (Köhler-Rollefson and Mathiasxii, 2010). Scientific research to harness these traits and promote these breeds among livestock farmers may prove beneficial as an adaptation strategy for the future. There is a need to re-imagine livestock development policies in a regional context beyond milk yield to consider these desirable traits for adaptation. As, in the case of Gujarat, about 50 per cent of the cost incurred on Animal Husbandry has been towards livestock health. Promoting locally adaptive breed with a greater focus on small ruminants can be a way forward towards climate change adaptation. Also, promoting locally available animal feed and fodder, kitchen wastes and roughages or adopting a

region-specific strategic feeding with respect to the livestock breeds of the region can reduce the dependence on expensive concentrate feeds.

Several adaptation strategies are employed, especially by the farmers in advanced countries, to ease the impact of climatic stress on livestock and arrest the decline in milk yield owing to heat stress. These strategies include shelter modifications to control the temperature-humidity indexes, installing proper cooling facilities, spraying evaporation cooling to regulate temperatures and nutritional management. However, such techniques are water-intensive, consume a significant amount of energy, and are not always viable options for small and marginal livestock farmers in India (as discussed above). On the contrary, traditionally, livestock rearers in India have used different local strategies to adapt to the changing warm and humid conditions, such as using natural trees and ponds as a source of shade and temperature control. They have used different coping mechanisms like selling stock, diversifying stock, and migration to survive drought spells. Climate change offers the agricultural and livestock sciences to understand and consider the systems relationships between bio-physical, biodiversity and socio-cultural components for resilience and sustainability. Climate-resilient livestock policies need to have a greater capacity for different knowledge systems and for including different stakeholders in the decision-making process.

Conclusion

This paper explores that although there is much discussion about the mitigation strategy involving the livestock, there is not enough attention to the adaptive strategy involving this sector, especially in the Indian context. In India, livestock assumes great significance in India's agricultural sector. Evidences suggest that farmers are already adapting to the changing climatic conditions because of its impact on the milk yield with increased temperature and humidity, especially in the coastal regions. However, given the resource constraints faced by landless, marginal and small farmers, who also form a substantial chunk of livestock rearers, it will not be easy to adapt to these changing climatic conditions without state support, both economically and in terms of knowledge sharing. The capacity of science to inform policy is important but the relationship between science and policy should not be limited to supply of technology for their uptake into the policy. Since, the relationship between science and policy is evolving and will continue to evolve. For adaptive policies and to build climate resilience, there is a need for an innovative process in science and policy relationships. A process that is dynamic in nature and involves an open dialogue and learning opportunities from and within sciences along with different forms of knowledge and values of different local communities and other stakeholders.

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Notes

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- ¹ "Adaptation is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this." (IPCC 2022, SPM-5, 7)
- ² The Indian Dairy Cooperation (IDC) was set up at Baroda, Gujarat by the Union government in 1970 to operationalise the OF and handle the gifted dairy commodities.

Exploring revealed comparative advantages and scientific collaboration in science and technology disciplines across CARICOM countries from 2000 to 2020

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Abstract

In this research, we aim to analyze the scientific system of the CARICOM countries. As a group of small states facing economic and fiscal challenges, high unemployment rates, and limited resources for science and technology, the region has unique characteristics that require a well-suited scientific system. Our study explores shared barriers and opportunities for development, including policy initiatives, remote work, and international research collaboration. We investigate the areas where CARICOM countries demonstrate boosting capabilities and the role of international research collaboration in scientific specialization. Our study proposes hypotheses on the impact of institutional incentives on researchers' participation in international collaboration networks and the relationship between scientific collaboration and specialization in small countries. We aim to provide useful and practical implications for research collaboration between small, geographically, and culturally proximate countries. To achieve this, we used bibliometric information from the Scimago database and the revealed comparative advantage approach to identify research domains where a country has a competitive advantage. Additionally, we identified specific research institutions that excelled in productive research

disciplines and interviewed their leaders to understand their success and whether their experience is replicable in other contexts.

1. Introduction

A constant trend during the last decades is the increasing role of science and technology in global competitiveness. Knowledge production requires at least expensive research infrastructures and skilled human resources in an adequate institutional context. Thus, only some countries can develop these settings for all research activities. That is especially true for less developed small countries, which must select key areas to concentrate their scarce resources. To face these barriers, globalization's increasing opportunities for international collaboration in research appear as an opportunity but also a threat for small countries. This work aims to analyze the situation of the CARICOM¹ countries' scientific system. This group of small states is geographically close to main research hubs such as the US and established historical and cultural ties with other research-intensive countries such as the UK, Netherlands, France, and other European countries. However, the CARICOM countries must catch up in research productivity compared to several regions worldwide, closing the gap with the developed countries in specific research areas.

The CARICOM Countries have specific and similar barriers that make it a worth investigating region in terms of developing a well-suited scientific system for its development path. After the 2012 world economic recession, The CARICOM countries experienced low economic growth rates. Also, an extraordinary economic downturn occurred during the pandemic, especially for those more tourism intense economies. An increase in the frequency of natural disasters and historically high public debt rates are also causes of endemic fiscal issues in the region, which restrict countries' investment in areas such as science and technology. With a few exceptions, unemployment is pervasive throughout these countries, especially youth unemployment which unfortunately ranks comparatively among the highest in the world, pushing local talents to pursue their careers abroad.

However, CARICOM countries have similar advantages for developing a scientific system that fits its unique characteristics. These advantages include geographical closeness and a common language (except Haiti and Suriname). Also, many policy initiatives were implemented to incentivize research activities in CARICOM: green and blue economy, climate-resistant infrastructure, big data and digital development, geothermal energy, and medical research programs focused on tropical viruses that can spread faster

internationally. Also, despite the obvious negative consequences, the COVID-19 pandemic opened a window of opportunity for the region with the explosion of remote work. Some CARICOM countries (especially Barbados) took advantage of the last by attracting specialists in IT areas who work remotely for the US or Europe to their unique landscapes. While the consequences of this strategy are still unknown for their STI system, other countries could have followed a similar approach.

These shared barriers and opportunities for the CARICOM countries open the need to investigate which research disciplines will require more effort for capacity building and those in which the region excels. However, despite their similarities, countries and even specific islands within CARICOM have their specificities. In this regard, it is essential to understand where the research capacities are located and the policy initiatives required for their development.

Descriptively, this research aims to show which research areas the CARICOM countries demonstrated boosting capabilities during the last two decades. Also, it becomes necessary to understand whether this path occurred homogeneously within CARICOM or was concentrated in specific countries. In this sense, research collaboration becomes central to our study: Do the disciplines that revealed advantages during the last decades emerge endogenously or result from increased international research collaboration? If so, does this process occur with CARICOM researchers having prominent roles in their networks or as subordinate actors? These are the questions this study intends to answer.

The study proposes a main hypothesis related to scientific collaboration and research outputs in small countries, specifically in the CARICOM region. This hypothesis includes the impact of institutional incentives on collaboration, the role of CARICOM researchers in international collaboration networks, the relationship between scientific specialization and collaboration, and the potential for scientific collaboration to drive specialization. The study aims to test this hypothesis and provide insights into the nature and dynamics of scientific collaboration in small countries. In a nutshell, the hypothesis that drives this paper is that because of CARICOM's institutional frameworks and scale, scientific specialization is related to research collaboration in small countries (CARICOM-like).

This research is significant for several reasons. Firstly, it represents the first attempt to explore research outputs and collaborative relationships in CARICOM countries. The last is important because it sheds light on the region's scientific and technological research capacity, which has been relatively understudied compared to other parts of the world. By identifying patterns in research collaboration and outputs, this study can better understand the strengths and weaknesses of the CARICOM countries' scientific and

technological sectors and help inform policies promoting research and innovation in the region.

In addition, this study fills a gap in the existing literature on collaboration at the country level. Most previous studies have focused on major economies and regions or collaboration between emerging economies such as the BRICS countries. By focusing on the CARICOM countries, this study provides insights into the specific challenges and opportunities faced by small countries that are geographically and culturally proximate. Such countries often face unique research collaboration and innovation challenges, for instance, limited resources, small research communities, and a lack of access to advanced technologies. By identifying the patterns and factors that facilitate or hinder research collaboration in the CARICOM region, this study can help inform policies and strategies to strengthen research and innovation in small countries.

2) Research collaboration: fundamental concepts and approaches

Defining research collaboration is not an easy task. Many characteristics of the process join two or more researchers to work side by side on specific projects. However, we may identify some of the basic aspects of this collective activity (Bukvova, 2010). First, it involves interactions between two agents that expect to obtain mutual benefits when developing scientific activities together. Second, it implies sharing information, resources, competencies, and ideas to create or potentiate current possibilities for research. Third, it could occur at different stages of the research process, whether it is the definition of the agenda, the development of actual research activity, or the closure of a research project. Furthermore, it should be retained as a social process in which institutional frameworks, routines, practices and habits play a fundamental role in orienting the alternatives to collaborate and determining their frequency and stability on time.

Research collaboration is a multilevel process; it can be observed at several levels and between different agents: researchers, laboratories, departments, organizations, disciplines, regions, countries, or a combination thereof (Beaver, 2001; Bukvova, 2010). As such, the complexity that emerges from this phenomenon tends to include a set of considerations that are not easily synthesized: it should consider the incentives placed at the individual level and those designed to create collaboration within and between different organizations. It should also include national and international agreements needed to preserve the rights of the people and environments where it takes place, including not only intellectual property issues but also ethics and law compliance to ensure the safety of the participants and their surroundings. When describing research collaboration axes, we would normally find (Bozeman & Corley, 2004; Bukvova, 2010): (i) the scientific background of the people involved (including their former studies and disciplinary experience);

(ii) their affiliations in institutional terms; (iii) the different level of organizational structure and; (iv) the implications of geography (related to the proximity of researchers but also the interaction with their local context).

International research collaboration is considered a strategy for developing scientific capabilities since it could create complementary relationships between agents placed in different regions that could contribute to closing gaps or offer resources that are not locally met (Chen et al., 2018; Luukkonen, 1992). The last is of utmost importance for developing countries since it is seen as a learning opportunity. When agents from countries that exhibit a less developed scientific system interact with those that belong to countries with a sound international position in knowledge generation and application, we expect the former to upgrade their capabilities through this interaction. It does not imply that more advanced countries do not benefit from this type of collaboration since they might gain access to the understanding of new problems, territories, and different types of knowledge that are locally determined.

We might identify two main patterns emerging from an international research collaboration between developing and developed countries (Bozeman et al., 2015; Walsh, 2007). On the one hand, we find the virtuous possibility of generating a mutual learning process where all participants build interactions that foster their scientific capabilities (opening up new topics, projects, and approaches to different issues, increasing resources of efficiencies in their use). On the other hand, we might find exploitation problems, where power relationships might imply that agendas are not connected to local needs or that externalities and side-effects of research are not fully considered in the collaboration design (Rikap & Lundvall, 2020). Moreover, of course, these two options have many intermediate scenarios. What is needed to overcome this collaboration's negative effects is an institutional framework that might guide it towards the most desirable state, including establishing academic institutions that anchor local development and configuring a set of policies that support their activity over time.

Measuring international research collaboration is challenging since no indicator (nor a set of them) is able to express this interaction's high degree of complexity (Bozeman & Corley, 2004; Chen et al., 2018). Nevertheless, even when it is not the only way to approach this topic, it is widely accepted that a reliable proxy for research collaboration is co-authored papers in which at least two authors are affiliated with organizations based in different countries. Research collaboration is normally expressed in scientific products that comprehend peer-reviewed papers in scientific journals, books (and book chapters) published by recognized institutions, reports, and a set of documents that codify the execution of this activity.

This research will use the Reveal Competitive Advantage (RCA) approach to assess the degree of collaboration between countries. RCA is an economic indicator proposed as a proxy of the relative advantage of a country in producing a specific product, given a set of products in the world or region of interest. We consider that by looking at the RCA of the collaboration process, we might observe how countries are prepared to interact in specific research areas. Our main assumption is that countries will exhibit a higher level of RCA on research collaboration because they are capable of undertaking research in those topics, which is a proxy of their scientific specialization. We will apply this concept to the co-authorship between countries of the CARICOM region to observe how they interact to foster their scientific capabilities.

3) The state of science and academic institutions in CARICOM: Progress and challenge

The state of scientific and academic institutions in the Caribbean Community and Common Market (CARICOM) varies significantly due to country size, economic status, and investment in research and education (Caribbean Development Bank, 2015). Therefore, some CARICOM countries may have well-established academic institutions and a strong research focus, while others may struggle with limited resources, insufficient infrastructure, and underdeveloped academic sectors (Hall & Guevara, 2016). Furthermore, despite having highly functional primary and secondary education systems, some countries may lack adequate resources and infrastructure to support higher education and research (Ottevanger et al., 2019).

Jamaica is the strongest country in academic terms, part of several well-respected academic institutions, including the University of the West Indies (UWI). UWI strongly focuses on research on climate change, sustainable development, and health and establishes partnerships with institutions worldwide,² providing students and researchers with opportunities for international collaboration and exchange. One notable example of UWI's international collaborations is its membership in the Association of Commonwealth Universities (ACU), a network of universities from Commonwealth countries. Through the ACU, UWI participates in various programs and initiatives to promote academic excellence and international cooperation. For instance, UWI has a strategic partnership with the University of Glasgow in Scotland, which includes joint research activities in areas such as climate change and renewable energy and student and staff exchanges (UWI, 2021). UWI also has partnerships with institutions in Canada, the United States, and China, among other countries (UWI, 2021).

Trinidad & Tobago is also home to several reputable universities, including the St. Augustine campus, one of the largest campuses of UWI. The University of Trinidad & Tobago (UTT) also offers degree programs in various fields,

including engineering, technology, and business. Trinidad & Tobago also has several research institutes, such as the Caribbean Industrial Research Institute (CARIRI), which provides research and development services to industries in the region. Barbados is another country in the Caribbean that has made progress in developing its academic and research institutions. UWI has a campus in Barbados that offers undergraduate and graduate degree programs in various fields, including the arts, sciences, and business. The campus also houses the Cave Hill School of Business, which provides training and development programs for executives and professionals.

A final notable country in the CARICOM is Guyana, home to the University of Guyana, which offers undergraduate and graduate programs in natural sciences, engineering, and humanities. The university has a strong research focus, with centers dedicated to biodiversity, renewable energy, and public health. Additionally, Guyana has several research institutes, such as the Guyana Forestry Commission, responsible for managing and conserving the country's environmental resources. These larger countries in CARICOM have invested heavily in education and research, developing strong academic institutions and centers that have significantly contributed to the scientific community and helped promote regional and international collaboration in research and development.

On the other hand, smaller countries in CARICOM, such as Grenada, St. Lucia, and Dominica, face considerable challenges in developing their academic and research institutions. These countries have limited resources for education and research, leading to underfunded and understaffed academic institutions. Consequently, they may experience difficulty recruiting and retaining highly qualified researchers and educators, which further compounds the issue of underdevelopment (Arthur & Murphy, 2016).

Moreover, limited infrastructure, such as inadequate laboratory facilities, hinders research capabilities in these smaller countries, making it more challenging to conduct research (Nembhard & Wright, 2019). The lack of investment in research also results in inadequate development of research expertise and outputs, such as patents and publications, which are essential for creating a vibrant research community (Caribbean Development Bank, 2015). These challenges result in a less developed academic sector in smaller CARICOM countries, which negatively impacts the quality of education and research, making it difficult for these countries to keep up with larger and more developed countries in the region.

4.1 Role of government

Government support is critical in developing science and academic institutions in CARICOM. Countries prioritizing research and development by establishing funding mechanisms for scientific research tend to have more successful

academic institutions. For example, Barbados and Trinidad and Tobago have established research and development funding mechanisms and have vibrant academic institutions. These countries attract top researchers and academics who bring knowledge and expertise and provide the resources necessary to conduct cutting-edge research in various fields. The government's support for research and development is critical for the success of the academic sector, which can lead to economic growth and development in the long run (UNESCO, 2021).

4.2 Collaboration

Academic collaboration between CARICOM countries has increased recently, with initiatives promoting collaboration among academic institutions. The Caribbean Research and Innovation Network (CaRiNET) is an initiative to foster collaboration among Caribbean research institutions (CaRiNET, 2021). CaRiNET provides a platform for knowledge sharing, exchange of ideas, and collaborative research projects. Additionally, the University of the West Indies (UWI) has established partnerships with several regional institutions, providing opportunities for academic collaboration and exchange of knowledge (UWI, 2020). Through such collaborations, academic institutions in the region can leverage each other's strengths and expertise to advance research and innovation.

The establishment of specialized institutions in specific areas of study has also enabled CARICOM countries to focus on areas where they have a comparative advantage, leading to the creation of new knowledge and technologies that have the potential to drive economic growth and development in the region. For example, Barbados has established the Caribbean Institute for Meteorology and Hydrology, a regional center of excellence in weather and climate science. In contrast, Trinidad & Tobago established the Caribbean Industrial Research Institute (CARIRI) to facilitate research and development in industrial technology and innovation research and development.

4.3 Challenges

There are major challenges facing science and academic institutions in the region. One major issue is funding, as many CARICOM countries have limited resources to invest in research and higher education, making it difficult to attract and retain talented researchers and educators and to provide students with adequate resources. Another challenge is brain drain, as many of the region's most talented scientists and academics have been lured away to work in other countries with more resources and better opportunities. The last can create a shortage of skilled professionals in some fields and limit the region's growth of science and academic institutions.

Table 1 – Documents, citations, and key economic indicators for the CARICOM countries

	<i>Scopus publications (2000-2020)</i>	<i>Citations (2000-2020)</i>	<i>GDP per capita (2020) constant prices</i>	<i>Population (2020)</i>
<i>Antigua & Barbuda</i>	212	2073	15486	92377
<i>Bahamas</i>	800	13562	27604	405779
<i>Barbados</i>	2424	77340	15606	280427
<i>Belize</i>	544	28142	5966	392426
<i>Dominica</i>	441	7400	7192	71764
<i>Grenada</i>	2110	26790	8510	123159
<i>Guyana</i>	779	11597	10659	791842
<i>Haïti</i>	1406	29826	1290	11234508
<i>Jamaica</i>	7008	124782	5292	2814473
<i>Montserrat*</i>	119	3728	15067	4555
<i>Saint Kitts and Nevis</i>	889	10723	19942	47681
<i>Saint Lucia</i>	171	6351	8170	178922
<i>Saint Vincent & the Grenadines</i>	132	2016	9654	104712
<i>Suriname</i>	597	12868	5387	603805
<i>Trinidad & Tobago</i>	7313	105812	14583	1513900

**GDP per capita (2020) CEPALSTAT, data from montserrat UNData*

Table 1 provides information on Scopus publications, citations, GDP per capita, and population for various Caribbean countries from 2000-2020. The data presented above provides insight into the state of science and academia in various Caribbean countries based on Scopus publications, citations, GDP per capita, and population. The Scopus publications data reveals that Jamaica, Trinidad and Tobago, and Barbados have the highest number of publications indexed in the database, indicating their potential as key contributors to scientific research in the region. Conversely, Montserrat, Dominica, Saint Vincent & the Grenadines have the lowest Scopus publications.

Citation analysis shows that Jamaica, Trinidad & Tobago, and Barbados have also received the highest number of citations for their publications, indicating the impact and influence of their research. In contrast, Montserrat, Dominica, Saint Vincent & the Grenadines have received the lowest number of citations, which could indicate a lower level of research impact and visibility in the international scientific community.

In addition to research output, the literature suggests that GDP per capita and population can influence a country's scientific and academic development. The data shows that the Bahamas, Saint Kitts and Nevis, and Montserrat have the highest GDP per capita, which could indicate the availability of resources to support research and development. Conversely, Haiti, Belize, and Suriname

have the lowest GDP per capita, which may limit their ability to invest in scientific research.

Finally, the data reveal that Haiti, Trinidad and Tobago, and Jamaica have the highest populations in the region. While a larger population can provide a larger pool of potential researchers and students, it can also present resource allocation and funding challenges for scientific research and education. On the other hand, Montserrat, Dominica, Saint Kitts & Nevis have the lowest populations, which may limit their scientific and academic capacity due to a smaller pool of human resources.

In summary, Table 1 shows that the Caribbean countries vary significantly in their scientific output, economic development, and population size. Jamaica and Trinidad and Tobago have the highest publications and citations, while the Bahamas and Saint Kitts and Nevis have the highest GDP per capita. Haiti has the largest population but the lowest GDP per capita. The data can be used to compare and analyze the research and economic performance of different Caribbean countries over the past two decades.

4) Data and methods

This research describes and explains the evolution of the CARICOM countries' scientific output in the last two decades. First, built on bibliometric information from the Scimago database for the 2000-2020 period, this study illustrates CARICOM's research output compared –in relative terms– to the world. Based on the well-known revealed competitive advantage approach (RCA), the inquiry establishes the research domains where a region or country shows an RCA. Nevertheless, more importantly, it shows how the regional and country-specific RCA evolved during the last 20 years. The previous exercise makes it possible to descriptively identify how the research capacities raised or declined during the period of interest.

The empirical tool helps identify an RCA in a research discipline if it has a greater participation in the national scientific production than the participation of that area in the world's scientific production. Published articles and citation measurements of the scientific output are presented for 27 research areas from the Scopus database in this research. Specifically, the RCA is defined as the quotient between the discipline's participation in the scientific output of a country and the participation of this same discipline in world scientific production. Formally,

$$RCA = (P_{is} * P_i) / (n_s * n_i)$$

Where P_{is} are publications in a research area s in country i , P_i is the total publications in country i , P_s is the publications in the subject area s worldwide, and P is defined as the publications worldwide. This indicator was also developed for citations, focusing on both cases comparing RCA for CARICOM countries and the specific countries of the region throughout the entire 2000-2020 period. In terms of its interpretation, a revealed comparative advantage in a country's discipline is found if the RCA's value is greater than 1 in a given year. Otherwise, it does not show a competitive advantage for that specific year.

Secondly, using the same database, we identify the specific research institutions that excel in research disciplines previously identified as the more productive in ACR. To go a step further in explaining the reasons for that success in such a deprived context for developing research capacities, the third goal of this research is interviewing leaders of the ACR's prominent research institutions and groups to understand their evolution. The last exercise aims to discern if the experience of prominent research institutions or groups is replicable in other ACR contexts.

5) Results

In our analysis, the CC gravitates toward medical, biological, and social research, with revealed at least competitive advantages in seven research domains for 2000-2020. These areas include agricultural and biological sciences, business, management and accounting, economics, econometrics and finance, environmental science, medicine, nursing, and social sciences. As it is possible to see in Annex 1, most of the mentioned research domains were consistently above the threshold of 1 during the entire study period. The two exceptions are business, management and accounting, and social sciences, fields above the threshold but with a decreasing tendency in 2000-2020. Contrarily, the area of immunology and microbiology is above the competitive threshold, showing increasing advantages during 2000-2020.

Table 2 – VCR by Scopus research domain, CARICOM

<i>Scopus research domains</i>	Revealed competitive advantage	VCR not conclusive	Revealed competitive disadvantage
<i>Agricultural and biological sciences</i>	XXX		
<i>Business, management, and accounting</i>	XXX		
<i>Economics, econometrics, and finance</i>	X		
<i>Environmental science</i>	X		
<i>Immunology and microbiology</i>			
<i>Medicine</i>			
<i>Nursing</i>			
<i>Social Sciences</i>			
<i>Arts and Humanities</i>		XXX	
<i>Dentistry</i>		XXX	
<i>Earth and planetary sciences</i>		X	
<i>Energy</i>			
<i>Multidisciplinary</i>			
<i>Pharmacology, Toxicology and Pharmaceutics</i>			
<i>Psychology</i>			
<i>Biochemistry, Genetics, and molecular biology</i>			X
<i>Chemical engineering</i>			X
<i>Chemistry</i>			X
<i>Computer science</i>			X
<i>Decision sciences</i>			X
<i>Engineering</i>			X
<i>Health professions</i>			X
<i>Material science</i>			X
<i>Mathematics</i>			X
<i>Neuroscience</i>			X
<i>Physics and astronomy</i>			X
<i>Veterinary</i>			X

**Results are based on VCR time series by area, Annex 1*

The research domains highlighted in yellow in Table 2 are those in which the VCR is inconclusive. The last means the CARICOM countries have shown relative advantages in these areas during some years in 2000-2020, while others do not. The research domains with inconclusive VCR include arts and humanities, dentistry, earth and planetary sciences, energy, multidisciplinary, pharmacology, toxicology and pharmaceutics, psychology, biochemistry, genetics and molecular biology, chemical engineering, chemistry, computer science, decision sciences, engineering, health professions, material science, mathematics, neuroscience, physics and astronomy, and veterinary.

The research domains highlighted in red in Table 2 are those in which the CC has a competitive disadvantage. These research domains can be divided into three major areas: First, one which is calculus-intensive, such as decision sciences, mathematics, physics, and astronomy; second, one where engineering excels, composed of computer science, engineering, and material science; Finally, another where there is a combination of applied chemistry and biology, such as biochemistry, genetics and molecular biology, chemical engineering, and chemistry. The CC has a competitive disadvantage in these research domains for 2000-2020.

Chart 1 – CARICOM – Total Documents Published by Country, 2000–2021

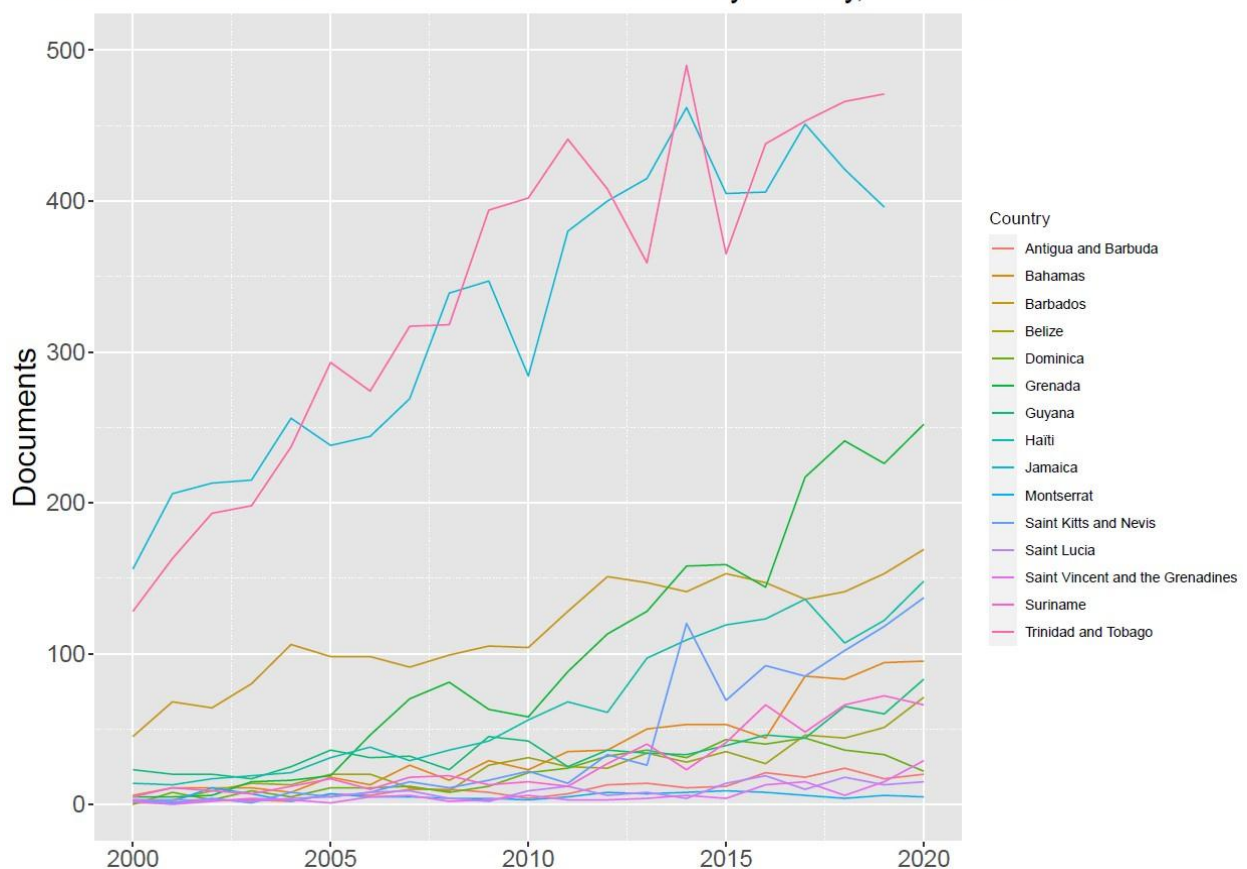


Chart 1 displays the evolution of documents produced by CARICOM countries. With few exceptions, all countries increased the number of documents produced during 2000- 2020. Another fact that arises from this indicator is the predominance of some "research hubs" in CARICOM: Jamaica and Trinidad & Tobago are the first countries in document production during the whole period. One step below, one can find Barbados. Also, it is possible to account for the recent and fast growth of Grenada and Saint Kitts & Nevis in document production at the end of the study period.

Table 3 – Key statistics of publication activity in Scopus in 2000, 2005, 2010, and 2020 in CARICOM countries

	Scopus documents as % of world documents(2000-2020)					Scopus documents as % of CARICOM documents (2000-2020)				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Antigua & Barbuda	0,00008	0,00035	0,00014	0,00034	0,00044	0,3	0,9	0,4	0,8	0,9
Bahamas	0,00045	0,00089	0,00082	0,00148	0,00207	1,5	2,2	2,1	3,5	4,5
Barbados	0,00340	0,00485	0,00373	0,00428	0,00368	11,4	12,2	9,6	10,1	8,0
Belize	0,00023	0,00099	0,00111	0,00098	0,00155	0,8	2,5	2,9	2,3	3,3
Dominica	0,00000	0,00054	0,00075	0,00120	0,00048	0,0	1,4	1,9	2,8	1,0
Grenada	0,00038	0,00094	0,00208	0,00445	0,00549	1,3	2,4	5,4	10,5	11,9
Guyana	0,00174	0,00178	0,00151	0,00109	0,00181	5,8	4,5	3,9	2,6	3,9
Haïti	0,00106	0,00154	0,00201	0,00333	0,00322	3,5	3,8	5,2	7,8	7,0
Jamaica	0,01178	0,01179	0,01019	0,01133	0,01099	39,4	29,5	26,3	26,6	23,8
Montserrat	0,00023	0,00035	0,00011	0,00025	0,00011	0,8	0,9	0,3	0,6	0,2
Saint Kitts and Nevis	0,00015	0,00025	0,00079	0,00193	0,00298	0,5	0,6	2,0	4,5	6,5
Saint Lucia	0,00023	0,00025	0,00032	0,00039	0,00033	0,8	0,6	0,8	0,9	0,7
Saint Vincent & the Grenadines	0,00015	0,00005	0,00022	0,00011	0,00063	0,5	0,1	0,6	0,3	1,4
Suriname	0,00038	0,00084	0,00054	0,00115	0,00144	1,3	2,1	1,4	2,7	3,1
Trinidad & Tobago	0,00967	0,01451	0,01442	0,01021	0,01099	32,3	36,4	37,2	24,0	23,8
CARICOM Total	0,02990	0,03991	0,03874	0,04253	0,04620	100,0	100,0	100,0	100,0	100,0

5 a) Key indicators CARICOM countries.

Table 3 exhibits the evolution of documents produced by CARICOM countries. The percentage of documents relative to those produced worldwide by specific years is shown on the left side of this table. Not surprisingly, the indicator shows the minimal share of each country and CARICOM's production in the world's output. However, an interesting fact is that between 2000 and 2020, CARICOM nearly doubled its document production from 0,029 to 0,046.

While looking at the right side of Table 3, it becomes clear that there are two major research centers within CARICOM: Jamaica and Trinidad & Tobago. In 2000, Jamaica participated in almost 40% of documents of these countries, while Trinidad & Tobago in 32,3%; however, these shares decreased to 23.8%. In this regard, the percentage of publications authored by researchers from several other countries has significantly increased within CARICOM since 2000 (except for Barbados, Guyana, Montserrat, and Saint Lucia). The last means that while Jamaica and Trinidad & Tobago can still be considered CARICOM's main research production hubs, other countries have increased their importance in research activities: Grenada and Saint Kitts and Nevis are the two most important cases, having increased their participation in CARICOM's research from 1.3 and 0.5 in 2000 to 11.9 and 6.5 in 2020 respectively.

5 b) Thematic profiles of CARICOM countries

Table 4 - CARICOM countries' ranking positions within CARICOM by the number of publications in Scopus subject areas

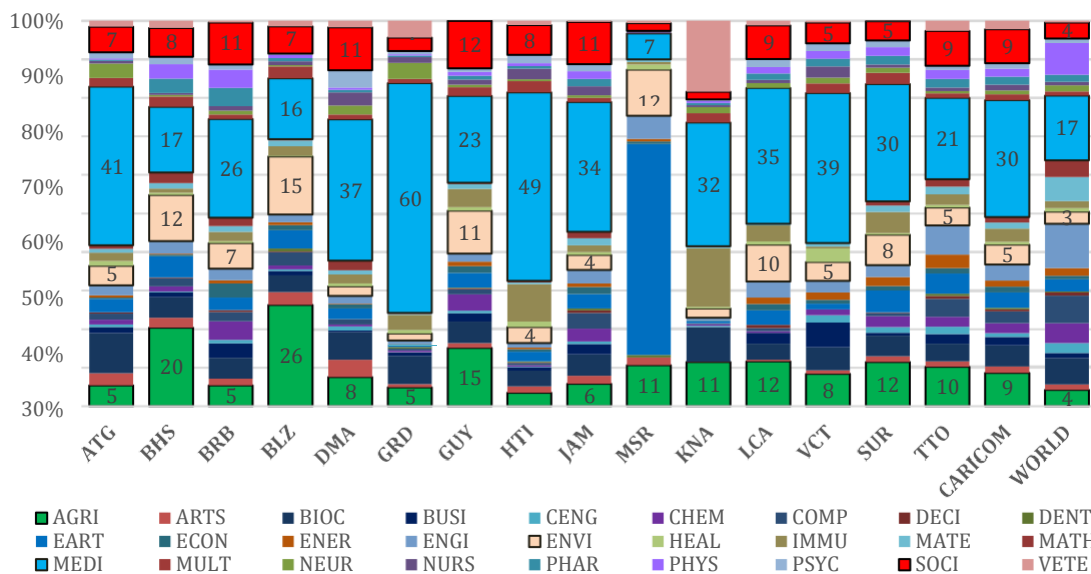
Country/ Area	AG RI	ART S	BIO C	BUSI	CEN G	CHE M	CO MP	DEC I	DE NT	EAR T	ECO N	ENE R	EN GI	ENV I
ATG	13	11	12	12	13	11	11	11	12	12	15	12	14	14
BHS	3	5	7	7	12	6	5	6	9	5	10	10	4	4
BLZ	4	7	11	9	11	9	4	9	4	9	7	7	9	6
BRB	5	3	4	3	3	3	3	3	7	3	3	3	3	3
DMA	11	6	10	13	6	12	9	12	13	10	9	13	10	13
GRD	8	8	3	5	8	7	7	10	3	11	8	11	8	9
GUY	6	9	8	4	5	4	6	4	6	8	4	5	6	5
HTI	10	4	6	6	10	8	8	5	5	6	5	6	7	7
JAM	2	1	1	2	2	1	2	2	2	2	1	2	2	2
KNA	7	14	5	14	7	10	12	13	14	14	12	15	13	10
LCA	12	15	14	11	14	14	13	8	11	13	11	8	11	11
MSR	15	12	15	15	15	15	15	15	8	4	14	14	12	12
SUR	9	10	9	10	4	5	10	7	10	7	6	4	5	8
TTO	1	2	2	1	1	2	1	1	1	1	2	1	1	1
VCT	14	13	13	8	9	13	14	14	15	15	13	9	15	15
Country/ Area	HEA L	IM MU	MA TE	MA TH	ME DI	MUL T	NEU R	NU RS	PHA R	PHY S	PSY C	SOC I	VET E	
ATG	12	13	12	12	11	12	8	13	8	14	11	13	10	
BHS	7	11	4	4	10	6	11	11	13	4	6	6	5	
BLZ	13	9	7	10	12	10	12	8	11	10	14	9	8	
BRB	5	6	3	3	5	4	4	4	5	3	3	3	7	
DMA	10	10	9	5	9	11	6	6	10	11	5	8	9	
GRD	4	5	11	8	3	7	1	5	6	8	7	7	3	
GUY	6	7	5	9	8	9	10	7	9	7	9	5	12	
HTI	3	3	8	7	4	3	9	3	3	6	4	4	6	
JAM	1	4	2	2	1	2	3	1	2	2	1	1	4	
KNA	9	2	10	11	6	5	5	9	4	9	12	11	2	
LCA	14	12	14	14	13	14	14	14	12	12	10	12	11	
MSR	15	15	15	15	15	15	15	15	15	15	15	15	15	
SUR	11	8	6	6	7	8	7	10	7	5	8	10	13	
TTO	2	1	1	1	2	1	2	2	1	1	2	2	1	
VCT	8	14	13	13	14	13	13	12	14	13	13	14	14	
* Abbreviations for 27 Scopus subject areas and for CARICOM countries are presented in the Annex note														

The countries' positions in a ranking within CARICOM by the number of publications in different Scopus subject areas are presented in Table 4. It is possible to note the leading positions of Jamaica and Trinidad & Tobago. Jamaica is the local leader in nine Scopus subject areas, while Trinidad &

Tobago led in 17 (out of 27 areas) during 2000-2020. Rarely these two countries are below the two first places in this ranking within CARICOM. The area where neither Jamaica nor Trinidad & Tobago leads is Neuroscience, a research field led by Grenada. It is also important to highlight some facts resulting from Table 4: Barbados comes third in 16 out of 27 areas, and Saint Kitts and Nevis occupy CARICOM's second position in the areas of "Immunology and Microbiology" and "Veterinary."

The Scopus' 27 subject areas classification was used to understand the scientific specialization of the CARICOM countries. The structures of publications were assessed according to the weight of these areas and compared with the world's publication structure. Then the countries' Relative Comparative Advantages Index (RCA index) was calculated.

Chart 2 – Publication area's structure, CARICOM



* Abbreviations for 27 Scopus subject areas and for CARICOM countries are presented in the Annex note

CARICOM's publication structure differs from the world's (Chart 2). This group of countries gravitates toward "Medicine" and "Agricultural and Biological Sciences" research, and to a less extent, "Environmental" and "Social Sciences." Worldwide, 17% of the publication structure is represented by Medicine, but this percentage rises to 30% in CARICOM's publication structure. The dominance in the publication structure of "Medicine" can also be seen in many countries of CARICOM. For example, this research area represents 60% of Grenada's publication structure, to mention the most salient case. Even in the region's more diversified cases and main research hubs, Jamaica and Trinidad & Tobago, "Medicine" represent 34% and 21% of the publication structure, respectively. Similarly, "Agriculture and Biological

Sciences" is around 9% of CARICOM's publication structure, representing 4% worldwide. Belize is the most prominent case in this research field, accounting for 26% of its publication structure. Several CARICOM countries show a higher concentration of their publication structure in "Environmental Science" compared to the world's structure. Belize, Bahamas, and Guyana show 15%, 12%, and 11% of their publication output concentrated in this field, while the world's output represents 1% of the total publication structure.

Table 5 – Correlation matrix of CARICOM countries' publication structures

	ATG	BHS	BRB	BLZ	DM A	GRD	GUY	HTI	JAM	MSR	KN A	LCA	VCT	SUR	TTO
ATG	1														
BHS	0,65	1													
BRB	0,92	0,71	1												
BLZ	0,53	0,96	0,58	1											
DMA	0,97	0,67	0,93	0,55	1										
GRD	0,98	0,75	0,89	0,67	0,96	1									
GUY	0,81	0,90	0,88	0,86	0,84	0,82	1								
HTI	0,97	0,58	0,91	0,47	0,96	0,98	0,79	1							
JAM	0,97	0,67	0,97	0,55	0,98	0,95	0,85	0,96	1						
MSR	0,12	0,32	0,12	0,30	0,10	0,05	0,22	0,08	0,12	1					
KNA	0,79	0,58	0,68	0,52	0,77	0,84	0,68	0,82	0,73	0,03	1				
LCA	0,95	0,80	0,94	0,70	0,94	0,95	0,92	0,94	0,96	0,18	0,78	1			
VCT	0,97	0,67	0,92	0,56	0,95	0,97	0,82	0,95	0,96	0,08	0,76	0,96	1		
SUR	0,94	0,81	0,92	0,72	0,93	0,95	0,91	0,93	0,93	0,24	0,79	0,98	0,94	1	
TTO	0,88	0,81	0,91	0,71	0,89	0,87	0,90	0,85	0,93	0,25	0,72	0,94	0,88	0,92	1

* Abbreviations for CARICOM countries are presented in the Annex note

While the publication structures of CARICOM countries are quite different from the world, they are similar among them. A correlation matrix of CARICOM publication structures helps corroborate how similar the CARICOM countries' publication structure dyads are. Notably, most correlations are above 0.7, meaning that CARICOM's publication structures are compatible, opening room to enhance academic collaborations. However, exceptions can be found. First, Montserrat shows the lowest correlation matrixes of CARICOM countries. This small island is still a British overseas territory whose publication structure is largely dominated by "Earth and Planetary Sciences" research produced in Montserrat's Volcano Observatory, which is unique in the region. Belize can be a second exception; this Central American country accounts for lower correlation matrixes than the other CARICOM countries (except Montserrat). It accounts for an important weight in its publication structure of "Agricultural and Biological Sciences" Research and "Environmental Science Research," two important fields also for CARICOM

countries: However, in Belize, these two areas largely dominate in its publication structure, opening an opportunity to be a major regional hub in these fields.

Table 6 - RCA Matrix, CARICOM countries (rows) Scopus research areas (columns), 2000-2020 trimmed mean (0,95)

Country	ATG	BHS	BRB	BLZ	DMA	GRD	GUY	HTI	JAM	MSR	KNA	LCA	VCT	SUR	TTO
AGRI	1,03	4,55	1,19	6,21	1,43	1,09	3,39	0,77	1,12	1,75	1,94	2,83	2,27	2,60	2,20
ARTS	1,27	0,98	1,08	1,70	3,16	0,57	0,53	1,02	1,11	0,31	0,00	0,00	0,12	0,64	0,90
BIOC	0,89	0,65	0,69	0,50	0,79	0,69	0,67	0,39	0,66	0,00	1,06	0,34	0,41	0,92	0,61
BUSI	0,52	0,98	2,94	0,72	0,11	0,73	1,38	0,47	1,63	0,00	0,00	2,33	6,72	0,48	1,87
CENG	0,05	0,03	0,30	0,04	0,13	0,02	0,23	0,02	0,19	0,00	0,02	0,00	0,24	0,33	0,68
CHEM	0,16	0,22	0,83	0,12	0,03	0,03	0,77	0,07	0,55	0,00	0,02	0,00	0,10	0,70	0,48
COMP	0,09	0,33	0,34	0,27	0,13	0,08	0,13	0,04	0,46	0,00	0,00	0,02	0,00	0,05	0,56
DECI	0,00	0,08	0,68	0,00	0,00	0,00	0,07	0,04	0,72	0,00	0,00	0,18	0,00	0,03	1,01
DENT	0,00	0,00	0,00	0,81	0,00	0,44	0,17	0,65	1,16	0,00	0,00	0,00	0,00	0,00	1,94
EART	1,21	1,36	0,85	1,60	0,65	0,06	0,92	0,59	0,97	13,00	0,08	0,55	0,17	1,86	1,45
ECON	0,00	0,64	3,88	1,17	1,02	0,28	1,55	0,84	1,62	0,00	0,03	0,41	0,00	0,69	1,52
ENER	0,21	0,02	0,46	0,17	0,00	0,00	0,35	0,15	0,41	0,00	0,00	0,25	0,15	1,27	1,84
ENGI	0,14	0,34	0,23	0,13	0,06	0,06	0,16	0,07	0,24	0,31	0,01	0,22	0,27	0,23	0,61
ENVI	0,89	3,49	1,88	4,75	0,53	0,33	2,80	1,05	1,00	2,82	0,44	2,68	1,38	1,72	1,34
HEAL	0,48	0,53	0,45	0,08	0,44	0,91	0,79	1,04	0,63	0,47	0,12	0,36	0,68	0,15	0,60
IMMU	0,70	0,37	1,21	1,08	0,73	1,57	2,35	4,34	0,74	0,00	5,05	1,46	0,00	2,37	1,38
MATE	0,07	0,24	0,21	0,14	0,06	0,01	0,17	0,05	0,24	0,00	0,01	0,00	0,00	0,20	0,30
MATH	0,13	0,54	0,50	0,03	0,31	0,04	0,05	0,03	0,30	0,00	0,01	0,00	0,00	0,14	0,37
MEDI	2,09	1,02	1,36	0,81	1,76	2,63	1,16	2,48	1,62	0,25	1,48	1,43	1,49	1,62	1,16
MULT	0,57	2,12	0,87	1,52	0,00	0,37	1,54	1,49	0,91	0,00	0,96	0,00	0,00	1,06	1,06
NEUR	1,12	0,12	0,54	0,17	1,21	1,52	0,19	0,23	0,30	0,00	0,65	0,29	0,28	0,50	0,33
NURS	0,15	0,20	1,21	0,66	2,75	1,10	1,14	2,85	2,25	0,00	0,29	0,00	1,59	0,32	0,92
PHAR	1,89	0,06	0,47	1,03	0,00	0,63	0,54	0,81	0,82	0,00	0,94	1,29	0,00	2,38	0,90
PHYS	0,00	0,33	0,51	0,08	0,02	0,02	0,10	0,07	0,18	0,00	0,02	0,09	0,37	0,19	0,26
PSYC	1,17	1,48	0,94	0,09	2,55	0,36	0,46	1,29	1,02	0,00	0,19	0,75	0,32	0,52	0,81
SOCI	0,97	2,29	2,51	1,78	2,93	0,88	2,47	1,59	2,21	0,20	0,82	2,31	1,28	0,93	1,99
VETE	3,69	5,09	0,78	1,97	1,88	5,75	0,00	1,54	0,43	0,00	31,13	1,06	0,00	0,00	4,62

* Abbreviations for 27 Scopus subject areas and for CARICOM countries are presented in the Annex note

In Table 6, we calculated the RCA trimmed mean of CARICOM countries in each of the 27 Scopus research fields for the entire 2000–2020 period. Since specific years in specific areas can be outliers for some CARICOM countries, we decided to use a trimmed mean at 0.95 to reduce its impact on the results shown in Table 6. In this table, quadrants with dark green are those fields where RCA is up to 1.5, and in light green are those where RCA is between 1.00 and below 1.5, meaning a very high and high specialization compared worldwide. In purple (RCA below 0.5) and pink (an RCA from 0.5 and below 1.00) are those research areas where CARICOM countries are less specialized than the world's publication production.

The prevalence of higher RCAs among CARICOM countries in the fields of "Agricultural and Biological Sciences," "Environmental Science," "Medicine," "Social Sciences," and "Veterinary" is manifest. Several CARICOM countries have shown a high RCA in these fields. Very high RCAs can also be found in "Arts and Humanities" in the case of Belize and Dominica and the fields of "Business, Management, and Accounting" for Barbados, Jamaica, Saint Lucia,

Saint Vincent and the Grenadines, and Trinidad & Tobago. Belize, Suriname, and Montserrat display a high RCA in "Earth and Planetary Sciences."

Guyana, Jamaica, Trinidad & Tobago, and particularly Barbados stand out with high RCA values in "Economics, Econometrics, and Finance." At the same time, Grenada, Guyana, Haiti, Saint Kitts & Nevis, and Suriname have very high RCA values in "Immunology and Microbiology." Bahamas, Belize, and Guyana strongly specialize in 'Multidisciplinary' fields. Dominica, Haiti, Jamaica, and Saint Vincent & the Grenadines have the highest RCAs among CARICOM countries in 'Nursing.' Suriname has the highest value of RCA in "Pharmacology, Toxicology, and Pharmaceuticals," and Antigua & Barbuda also stand out with high RCA values in this field.

Some CARICOM countries show especially high values of RCA in specific subject areas that the rest of CARICOM countries could not achieve. Grenada in "Neuroscience" is a special case; only two CARICOM countries could achieve RCAs above the threshold in this domain. Another case to highlight is Dominica in Psychology, where four CARICOM countries revealed weak competitive advantages. Finally, Trinidad & Tobago is the only country with a high RCA in "Dentistry" and "Energy," research fields in which Jamaica and Suriname revealed weak advantages. Trinidad & Tobago is the country within CARICOM that accounts for more research areas in which at least a weak RCA is shown (13). In this regard, Trinidad & Tobago is followed by Belize (10), Haiti (10), and Jamaica (10).

Another key fact emerges from Table 6. There are research areas in which no one of the CARICOM countries has shown RCAs above the threshold of one. That is the case of "Chemical Engineering," "Chemistry," "Computer Science," "Engineering," "Materials Science," "Mathematics," and "Physics, and Astronomy." Also, except for only one CARICOM country, in the fields of "Biochemistry, Genetics, and Molecular Biology," "Decision Sciences," and "Health Professions," RCAs were below the threshold of one. Thus, it is important to note that 9 out of 27 research fields in CARICOM could lack publications, which is our proxy of research production.

5 c) International cooperation between CARICOM countries

Table 7 - Documents published by authors of specific dyads of CARICOM countries, 2000 - 2020

A)	ATG	BHS	BRB	BLZ	DMA	GRD	GUY	HTI	JAM	MSR	KNA	LCA	VCT	SUR	TTO
ATG	0														
BHS	4	0													
BRB	10	24	0												
BLZ	2	5	14	0											
DMA	10	2	13	2	0										
GRD	8	2	18	4	11	0									
GUY	3	3	10	4	2	3	0								
HTI	1	4	14	7	1	1	2	0							
JAM	8	47	162	9	11	15	11	15	0						
MSR	0	0	0	0	1	0	1	0	1	0					
KNA	9	9	13	5	14	6	3	4	11	0	0				
LCA	7	3	14	3	13	8	2	0	17	0	4	0			
VCT	4	11	17	5	6	4	2	4	12	0	11	7	0		
SUR	2	6	7	6	2	7	41	1	8	0	1	1	1	0	
TTO	10	28	132	10	17	29	43	11	255	29	13	21	16	17	0
B)	ATG	BHS	BRB	BLZ	DM A	GRD	GUY	HTI	JAM	MSR	KNA	LCA	VCT	SUR	TTO
ATG	0%	3%	2%	3%	10%	8%	2%	2%	1%	0%	9%	7%	4%	2%	2%
BHS	5%	0%	0%	7%	2%	2%	2%	6%	8%	0%	9%	3%	11%	6%	4%
BRB	13%	16%	0%	18%	12%	17%	8%	22%	28%	0%	13%	14%	17%	7%	21%
BLZ	3%	3%	3%	0%	2%	4%	3%	11%	2%	0%	5%	3%	5%	6%	2%
DMA	13%	1%	3%	3%	0%	0%	2%	2%	2%	3%	14%	13%	6%	2%	3%
GRD	10%	1%	4%	5%	10%	0%	2%	2%	3%	0%	6%	8%	4%	7%	5%
GUY	4%	2%	2%	5%	2%	3%	0%	3%	2%	3%	3%	2%	2%	41%	7%
HTI	1%	3%	3%	9%	1%	1%	2%	0%	3%	0%	4%	0%	4%	1%	2%
JAM	10%	32%	38%	12%	10%	14%	8%	23%	0%	3%	11%	17%	12%	8%	40%
MSR	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	5%
KNA	12%	6%	3%	7%	13%	6%	2%	6%	2%	0%	0%	4%	11%	1%	2%
LCA	9%	2%	3%	4%	12%	8%	2%	0%	3%	0%	4%	0%	7%	1%	3%
VCT	5%	7%	4%	7%	6%	4%	2%	6%	2%	0%	11%	7%	0%	1%	3%
SUR	3%	4%	2%	8%	2%	7%	32%	2%	1%	0%	1%	1%	1%	0%	3%
TTO	13%	19%	31%	13%	16%	28%	33%	17%	44%	91%	13%	21%	16%	17%	0%
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

* Abbreviations for 27 Scopus subject areas and for CARICOM countries are presented in the Annex note

Table 7 shows a matrix showing documents published by authors of specific dyads of CARICOM countries (7a) and the relative weight of these dyads in the total CARICOM collaborated publications (7b) by country. Regarding the absolute total regional collaboration (Table 7a), Jamaica-Trinidad & Tobago seems the most fecund dyad of CARICOM. The last is not surprising since the

importance of both countries as the main research hubs regionally. Also, both countries show a proliferant collaboration with Barbados. The partnerships between Jamaica and Bahamas, Guyana and Trinidad & Tobago, and Suriname and Guyana have also demonstrated fructiferous outcomes for CARICOM.

In Table 7b, it is clearly shown that Trinidad & Tobago is the main hub for academic collaboration regionally. Thirteen out of fourteen CARICOM potential partners have Trinidad & Tobago as its first or second most important partner. Interestingly, a second important hub for academic collaboration is Barbados. Eight out of fourteen potential CARICOM collaborator countries have this Barbados as its most or second most important collaborator; four countries have Jamaica as its most important collaborator, and just one as its second. Outside these cases, other important dyads of collaboration to consider are Guyana-Suriname and, to a lesser extent, Dominica-Saint Kitts and Nevis.

6) Conclusions and limitations

Our analysis found that the CC has competitive advantages in several research domains, including agricultural and biological sciences, business, management and accounting, economics, econometrics and finance, environmental science, medicine, nursing, and social sciences. We also found that the CC has a competitive disadvantage in research domains that are calculus-intensive, engineering-focused, and have a combination of applied chemistry and biology.

Furthermore, our analysis revealed that CARICOM countries had increased their document production over the past two decades, with Jamaica and Trinidad & Tobago being the main research hubs. However, other countries within CARICOM, such as Grenada and Saint Kitts & Nevis, have also increased their participation in research activities.

The scientific specialization of CARICOM countries focuses on medicine and agricultural and biological sciences. However, CARICOM's publication structure differs significantly from the world's, with a lower emphasis on other areas such as engineering and physics.

Overall, our analysis provides valuable insights into the research landscape of CARICOM and highlights areas of competitive advantage for the region. These findings can inform policymakers and regional researchers to make informed decisions regarding research funding and priorities.

The analysis has limitations, mainly due to biases in the data source and the focus on successful research groups. Despite the heterogeneity in research capacities across CARICOM countries, some areas lack research capacities, which raises important questions for policy decision-making. Should the region

enhance deprived research areas in all CARICOM countries or focus on interchanging knowledge and professionals in specialized areas?

The research also identifies two patterns in CARICOM countries regarding research capacities: an academic institution that articulates different areas and a profile with an extractivist focus. These patterns are identified through network analysis and content analysis, providing further insights into the dynamics of research capacities in the region.

To deepen our understanding of these patterns, we propose conducting network analysis to identify researcher collaborations and bibliometric analysis for identifying patterns in scientific publications. Moreover, we recommend contextualizing the findings concerning the research question and the existing literature, drawing comparisons with relevant studies, and elaborating on the implications for policy and future research directions.

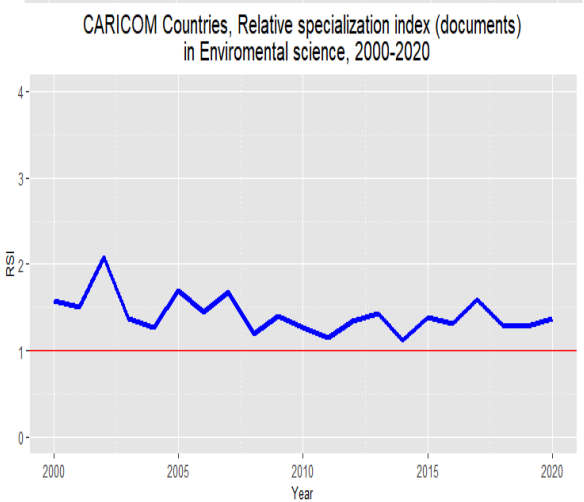
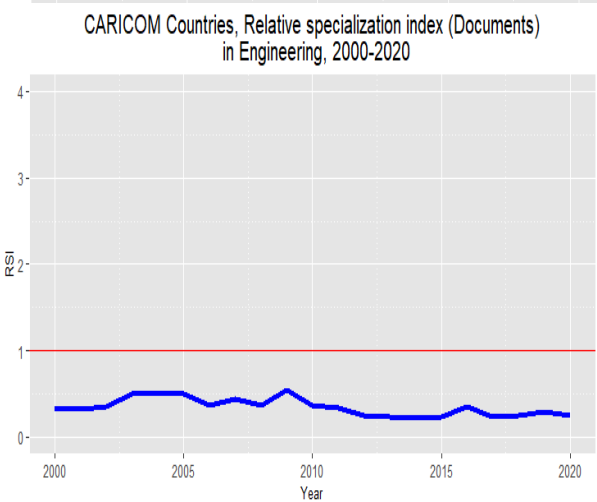
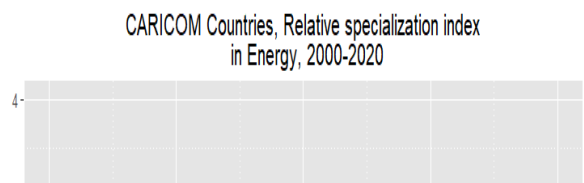
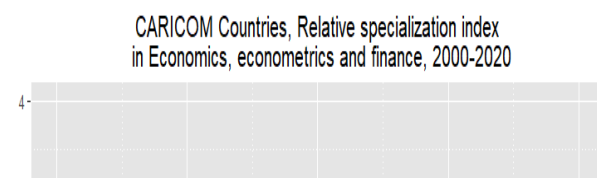
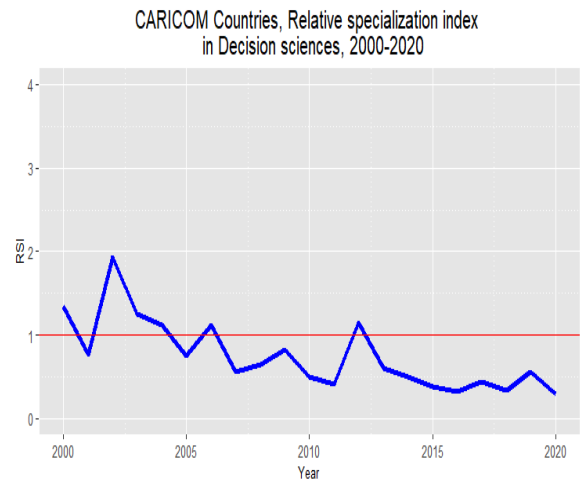
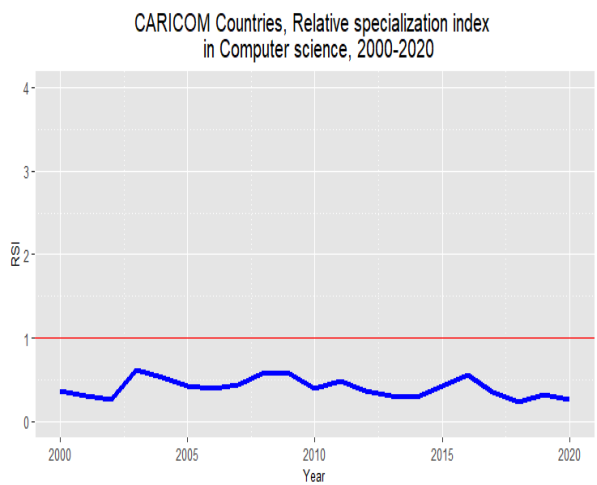
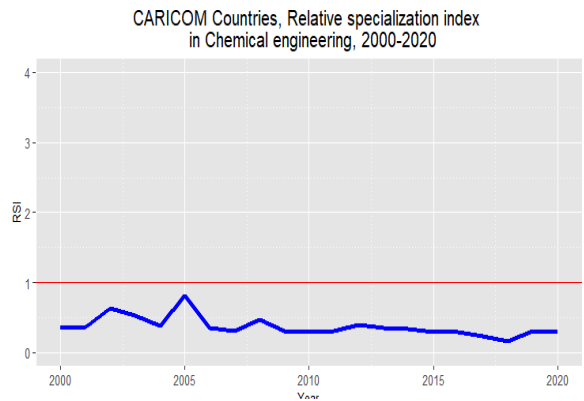
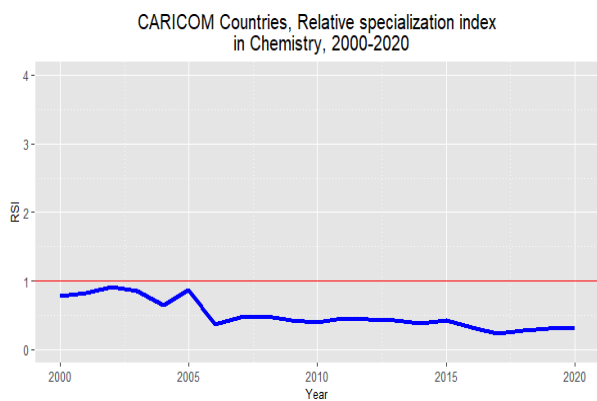
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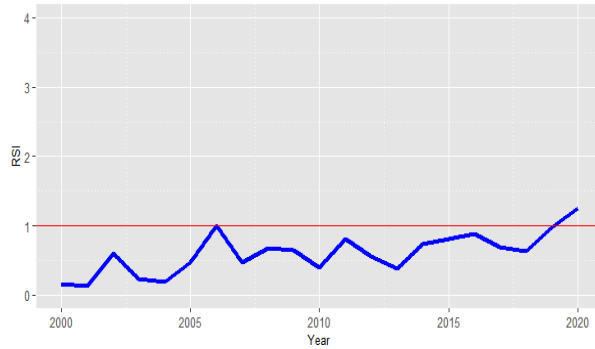
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Annex 1 - VCR for CARICOM countries by Area

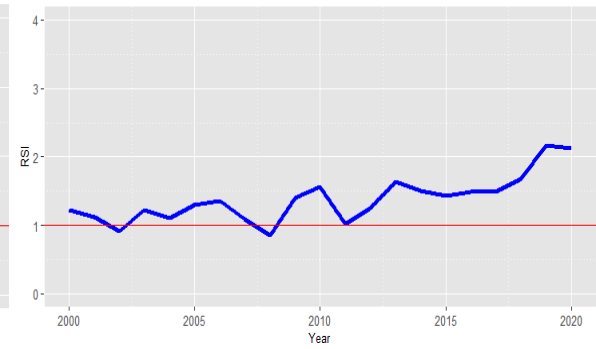




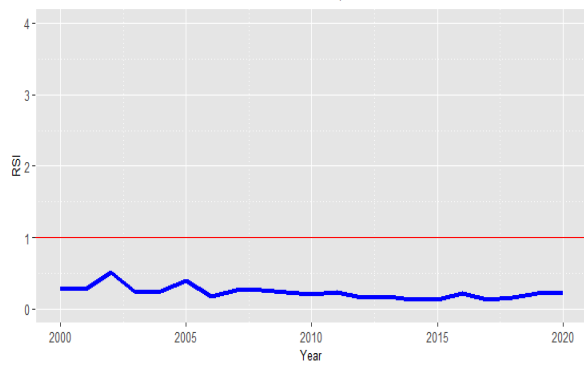
CARICOM Countries, Relative specialization index (Documents)
in Health professions, 2000-2020



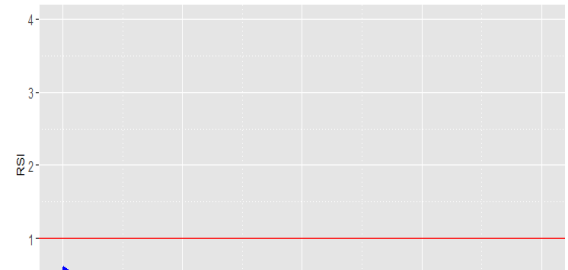
CARICOM Countries, Relative specialization index (Documents)
in Immunology and microbiology, 2000-2020



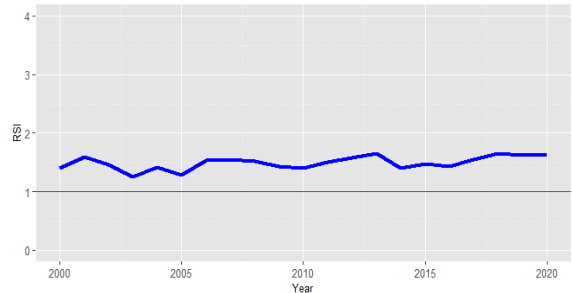
CARICOM Countries, Relative specialization index (Documents)
in Material science, 2000-2020



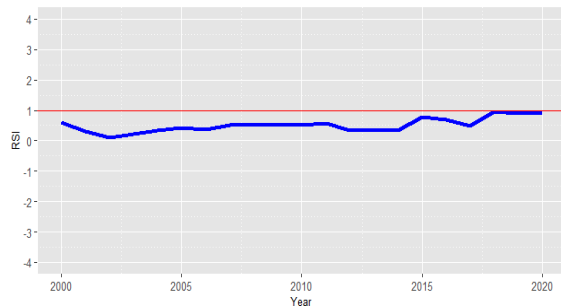
CARICOM Countries, Relative specialization index (Documents)
in Mathematics, 2000-2020



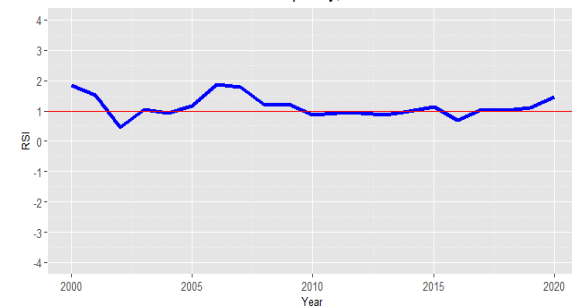
CARICOM Countries, Relative specialization index (Documents)
in Medicine, 2000-2020

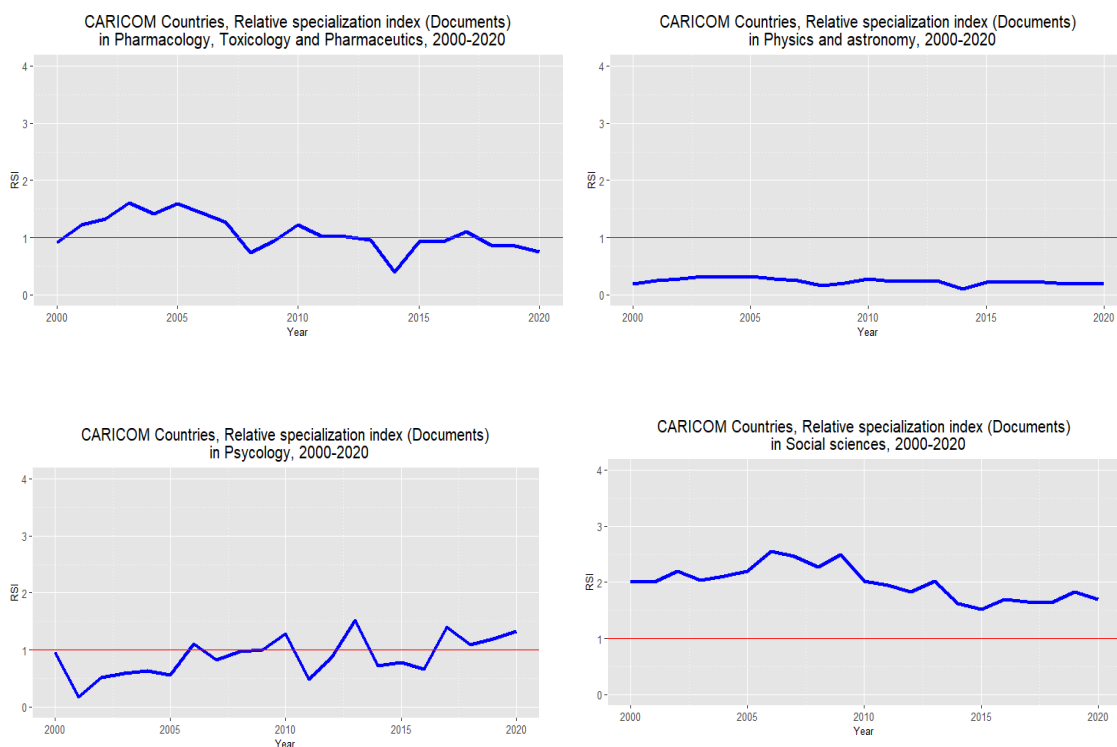


CARICOM Countries, Relative specialization index (Documents)
in Neuroscience, 2000-2020



CARICOM Countries, Relative specialization index (Documents)
in Multidisciplinary, 2000-2020





Scopus research areas abbreviations:

AGRI: Agricultural and Biological Sciences; ARTS: Arts and Humanities; BIOC: Biochemistry Genetics and Molecular Biology; BUSI: Business, Management and Accounting; CENG: Chemical Engineering; CHEM: Chemistry; COMP: Computer Science; DECI: Decision Sciences; DENT: Dentistry; EART: Earth and Planetary Sciences; ECON: Economics, Econometrics and Finance; ENER: Energy; ENGI: Engineering; ENVI: Environmental Science; HEAL: Health Professions; IMMU: Immunology and Microbiology; MATE: Materials Science; MATH: Mathematics; MEDI: Medicine; MULT: Multidisciplinary; NEUR: Neuroscience; NURS: Nursing; PHAR: Pharmacology, Toxicology and Pharmaceutics; PHYS: Physics and Astronomy; PSYC: Psychology; SOCI: Social Sciences; VETE: Veterinary

CARICOM countries ISO 3166 – CODES

ATG: Antigua & Barbuda; BHS: Bahamas; BLZ: Belize; BRB: Barbados; DMA: Dominica; GRD: Grenada; GUY: Guyana; HTI: Haiti; JAM: Jamaica; KNA: Saint Kitts & Nevis; LCA: Saint Lucia; MSR: Montserrat; SUR: Suriname; TTO: Trinidad & Tobago; VCT Saint Vincent & The Grenadines

Notes

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- ¹ Antigua & Barbuda, Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & the Grenadines, Suriname, Trinidad & Tobago
 - ² These partnerships provide UWI researchers access to funding, expertise, and resources unavailable within the region. They also facilitate collaboration and knowledge exchange between UWI and international partners, allowing the university to stay at the forefront of research and innovation in its focus areas. UWI's commitment to research and international partnerships has earned the university a strong regional and international reputation. Its faculty and students regularly publish in top-tier scientific journals, and the university has been recognized for its contributions to scientific knowledge and innovation. As a result, UWI is a leading destination for students and researchers seeking high-quality education and research opportunities in the Caribbean.

Knowledge-based inclusive transformation of rural areas in algeria the programme for integrated rural development

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MAGHTEH, Algeria

Abstract

To accelerate rural development, Algeria decided on a major programme, the Agricultural and Rural Renewal Policy (ARRP) divided into two sub programmes: the Agricultural Renewal Policy (ARP) and the Rural Renewal Policy (RRP). While , they are both based on intensive learning and knowledge approach, the Rural Renewal Policy (RRP) appears to mobilise Innovation as an engine to integrate knowledge based growth one of the sector. One of its “flagship” instrument was the Proximity Programme for Integrated Rural Development (PPDRI) which was made of hundreds of outreach projects expected to help rural populations strengthen their basic economic activities. The new Knowledge-Based Economy put forward by the State ambitioned to support this programme and make it more participatory and inclusive. While the PPDRI seems to have been adopted by large sections of the rural areas, its effectiveness is largely questioned particularly in the literature. Our papers address four key questions: 1/ How does innovation driven knowledge economy manage to contribute to the tranformative policy adopted by authorities in Algeria 2/how did that reflect through the new policy of the Agricultural through innovation driven KE policy? 3/ What were the obstacles met in its implementation? To answer these questions, five case studies drawn from the literature were analysed in three wilayas (prefectures) of the country in addition to the observant participant methodology adopted. This approach of examining rural development programme through the lens of innovation driven KBE policy has never been used before and represents the originality of our work and its main added value. The other contribution is conceptual: revisiting original KBE model

by adding the participation/ inclusion dimension when applied to rural development.

Keywords: Rural development, DS, Algeria, Science Technology and Innovation, knowledge-based economy

Introduction

Growth in the last decades has not translated been to lift millions of Africans out of poverty and reduce the wide inequalities and exclusion of rural populations (OECD 2006). Stieglitz (2005) proposed a strong government intervention through a combination of macro and micro policies. Thus, the State came about as a necessity (Johnson 1994) as it is the case in many in several African countries in the post-colonial era back in the sixties when the major objectives set up the new and often inexperienced governments were the construction of Nation States both from the political and economic point of views.

Since then, the State has been playing a key role in guiding economic development trying to balance economic growth and social development sometimes under the pressure of international organisations to comply with the structural adjustment programme (SAP) and the regulation myth (Bracking 1999) which drove large section of the population specifically in rural areas to fall into the extreme poverty as it did in Algeria in the nineties (Rastoin & Benabderrazik 2014). To overcome these problems, Algerian authorities put up a new policy, the Agricultural and Rural Renewal (RRA¹) policy based on an innovative approach to rural development targeting primarily rural populations living in difficult conditions in mountains, steppes and the sahara (MADR 2008). The Agricultural and Rural Renewal Policy (ARRP) was made of two policies: the Agricultural Renewal Policy (ARP) and the Rural Renewal Policy (RRP). While , they are both based on intensive learning and knowledge approach, the Rural Renewal Policy (RRP) appears to mobilise Innovation as an engine to integrate knowledge based growth one of the sector. One of its “flagship” instrument was the Proximity Programme for Integrated Rural Development (PPDRI) which was made of hundreds of outreach projects expected to help rural populations strengthen their basic economic activities. To implement the rural, a newly conceived instrument the Proximity Programme for Integrated Rural Development (PPDRI)² was adopted. It was an integrated rural development outreach program expected to fulfill the needs of rural populations by consolidating their basic economic activities and expand to other innovative ones. For the first time, the Ministry of Agriculture and Rural Development (MADR) mobilized Science, Innovation driven knowledge-based economy (KBE) approach to address problems met by rural populations

(OECD 2006) and in particular establish innovative pro-poor policies and foster more inclusive development in rural areas (IFAD 2015). The basic premise was that the knowledge divide is at the root of the development divide.

Four questions are addressed in our contribution: 1/ How does IKBE policy connect with the rural renewal policy? 2/ What level of participation of rural populations to this KBE based PPDRIs and how inclusive had it been ? To answer these questions a large survey of the literature was conducted and both primary and secondary data were used. The first category was first-hand information resulting from the participant observation methodology as the author was involved in the KBE approach at Ministry level (2006-2008). This was coupled with extensive documentary search from both internal sources (essentially the MADR) and international sources (IFAD, FAO, ASTI etc.). In the second category, five case studies well documented in the literature were analysed through the lens of IKBE approach in five wilayas (regions) of the countries which were amongst the first to implement the PPDRIs. Further details will be given regarding these cases in the empirical section. This approach has never been used in the existing evaluations of the PPDRIs and rural development in general in the literature and represents an added value and a valuable new insight for both policy makers and researchers. Section II looks at the Innovation driven Knowledge Economy policies for agricultural and rural development from a theoretical and conceptual point of view. Section III examines the Rural Renewal Policy and its flagship programme the PPDRIs as an instrument of to transform structurally rural areas through new policy instruments. Section IV examines empirically to what extent the level the IKBE approach succeeded in enhancing the participation of rural population through the empirical section and field results and section five discusses the results and concludes.

II - The IKBE policies for agricultural and rural development

2.1. The IKBE put in historical Algeria.

Algeria eagerness to develop an integrated economy free from any external dependant ties finds its roots in the bitter struggle against the French colonizer followed by a strong voluntarist attitude geared towards acquiring its "economic independence" following political sovereignty³. The planned economy system adopted gave the State a prominent role in the development of the country and the necessary authority (Johnson 1994) . This materialized through the adoption of four successive development plans: (1965-1967, 1967-1973, 1973-1977 and 1979-1982) geared towards setting a strategy of unbalanced growth (Hirschman 1958) and industrialization⁴ through forward and backward linkages (Perroux 1950, De Bernis 1963) in the context of import-substitution model. It used massively imported technology from abroad (Djefflat and Oufriha 1990) thanks to important oil revenues. This economic

regime came to a brutal end with the oil crisis of the eighties and the debt crisis leading to massive unemployment (Valensisi & Davis, 2011) and explosion of poverty following a SAP imposed by the World Bank and IMF (World Bank 2014). The poverty line reached \$ 3.18 in rural areas (poverty rate of 4.8%) with a Gini index of 27.61 (Ibarra and Atamanov 2017). The rural Human Development Index (0.3) was half the of the national one (0.6) (MADR 2006) and rural unemployment went from 23% in 1977 (Fontaine, 1983) to nearly 53% in 2008 (DPAT, 2008) with the food bill reaching 7.71 billion US dollars in 2008 (Lebeche 2011). The new policy started in 2000 was therefore to turn to its neglected agricultural and rural sector using a modern approach based IKBE. This is what we will examine in the next section.

2.2. The IKBE policy

The approach used to set-up a conceptual base for the Rural and Agricultural Renewal (RRA) policy has both S&T and KBE components (figure 1). This was one of the priority areas that the Algerian State decided to pursue in order to optimise its efforts and resources for rural development and structural transformation. Both, the IKBE components will be examined in depth in the next paragraphs.

2.2.1. The science technology and innovation policy adopted

Innovation and development field has known a growing interest in recent years essentially to address the issue why the various STI policies implemented by Governments in the South have failed to impulse innovation as engine of growth. Several problems were highlighted in the literature : vulnerable and unstable macroeconomic environment (Cassiolato and Lastres, 1999) the North-South innovation gap (Arocena and Sutz 2000), the inability of local institutions to interact with productive ones (Oyelaran-Oyeyinka, 2004, Wangwe, 2003) and the difficulties in establishing structured National Systems of Innovation often built ex post (Lundvall et al 2002). Most of these elements are found in the Algerian experience.

2.2.2. The Innovation driven knowledge-based economy paradigm

However, the question of knowledge has ancient origins. Since the emergence of classical economic theory in the 18th century, economists have sought to determine the sources of economic growth, beginning with Adam Smith's examination of the division of labor in *The Wealth of Nations* in the late 18th century.), to Karl Marx (middle of the 19th century) to the analysis of Joseph Schumpeter (1919,1935 on the importance of innovation in capitalism in the middle of the 20th century ; After World War II, Robert Solow (1956) offered a unified analytical framework, according to which economic growth is ultimately determined by exogenous extra-economic factors such as technological progress. The need to assess the importance of technological progress for sustainable growth, including related investments such as

education, has given impetus to new theories of growth in which technological progress is endogenously determined (Romer 1993, Romer, 1994). Finally, with the work of evolutionists, innovation is put 'out of the market' and penetrates the universe of institutions: it is at the heart of multi-actor interactive processes that almost definitively establish the systemic vision (Nelson and Winter, Christopher Freeman, Bengt-ake Lundvall etc.).

Several contributions have indicated that we are indeed in the economy knowledge since the end of the last century (Drucker 1994). World economy has undergone a radical change in which the scarce resource became knowledge and not mineral resources. From a conceptual point of view, Knowledge as public good with its main attributes of non-excludability and non-rivalry (Stiglitz 1999) is expected to accelerate development and growth (Foray 2009, Mansell 2009, Liaqut and Anders 2015). Knowledge is difficult to control; it spreads and is used by third parties without compensation by the authors. So there are positive externalities. But according to Kenneth Arrow (1962) knowledge is not identified with information. Information is made up of a stream of messages that exist independently of the individuals in knowledge, on the other hand, requires cognitive activity on the part of the agent who selects, processes and interprets messages to produce new ones; For Foray D. (2001)⁶ knowledge has something more than information because it generates new knowledge. For Mansell and Steinmueller (2000), it is a capacity learning and a cognitive process while information is limited to a set of structured data that cannot generate new information. Thus, the information exists independently of individuals while knowledge remains attached to people.

The 'knowledge in action' vision and the learning process (Bruckmeier and Tovey, 2008) contribute to forge the knowledge for development (K4D) vision developed mainly by the World Bank (Stiglitz 1999, Rischard, 2002).

Knowledge based economy framework of four pillars adopted : innovation, education, ICTs and institutions (Dahlman 2003) was expected to achieve simultaneously 'balanced' economic development, social inclusion and environmental protections through dedicated policy instruments and knowledge networks at the local level (Conteh 2012). This was helped by the relatively user-friendly instruments, the Knowledge Assessment Methodology S(KAM) used by WBI to rank various countries in the world on the knowledge economy index (KEI) (Chen and Dahlman 2006). KBE success rests upon a high level of interaction and interactive learning between the different spheres. We will see in practical terms how these interactions took place in Algeria in the next section.

Innovation driven versus knowledge driven growth: In innovation-drive knowledge economy refers to an economic system that places a strong emphasis on generating and utilizing knowledge and innovation as key drivers of growth and development. In this type of economy, the production and application of

knowledge, as well as the ability to innovate, are considered crucial for competitiveness and sustainable economic success.

From a structural perspective, the discussion of the roles of knowledge base in innovation-driven growth is relatively rare (Yu and Yan 2021). Mina et al. (2014) that successful companies have the following common features: they are good at searching widely for external knowledge and making full use of multi-source Knowledge. In order to develop new product distribution channels, processes, and services, it is necessary to increase the diversification of internal and external resources. The capability of a broad external knowledge search contributes to the innovation of business models. Led by a specific innovation strategy, knowledge-based innovation can play a better role and initiate innovation activities effectively. (Yu and Yan 2021). They found that (1) technological innovation relies more on knowledge depth than breadth; (2) knowledge depth and breadth jointly drive business model innovation; and (3) explicit character could significantly strengthen the effect of knowledge breadth on business model innovation. Knowledge base, both breadth and depth, makes a positive impact on the innovation-driven growth of an enterprise.

At macro policy-level, successfully inserted countries in IKBE are listed in the literature ; South Korea, Ireland, Chile, Malaysia amongst others. They all have in common the key rôle played by the State.ion of (to a lesser extent) : (A) the development of human capital and the preservation of knowledge assets' value are the ultimate function(s) of the knowledge economy, (B) learning, education, ICT, and innovation are the main pillars of the knowledge economy, (C) knowledge management at the company level is the underlying process of the knowledge economy function, and (D) beliefs and attitudes are the main endogenous drivers of individual engagement towards the ultimate functions of the knowledge economy. Yet , there is no single model, and each country, based on its development status, cognitive abilities, and ambitions, will define its own model. Dahlman (2005) indicated that India, with optimal utilization of its knowledge potential, can improve its total factor productivity from 2.09% in 2005 to 4.29% by 2020, and the GDP per capita will reach \$2,700. However, if the total factor productivity remains at the current level, the GDP per capita will be less than \$2,000. We define it in our work as an innovation policy embedded in a much broader knowledge economy policy, that coevolves simultaneously with education and training policy, a digitization policy and institutional reforms policy.

Innovation-driven, knowledge based agricultural policy:

Innovation-driven knowledge-based agriculture refers to an approach to agriculture that emphasizes the application of innovation and knowledge-based solutions to enhance productivity, sustainability, and overall performance in the agricultural sector. It involves the integration of scientific

research, technology, and information systems with agricultural practices to drive advancements and optimize agricultural outcomes. The European perception of this link between innovation and Knowledge materializes in the AKIS concept (Agricultural Knowledge and Innovation Systems (EU-SCAR⁵ 2015) gives some elements regarding innovation driven knowledge-based agricultural model. In this mode, innovation is 'co-produced' thanks to interaction between farmers, firms, researchers, intermediate actors (advisors, input providers, experts, distributors, etc.) and consumers in concrete projects.

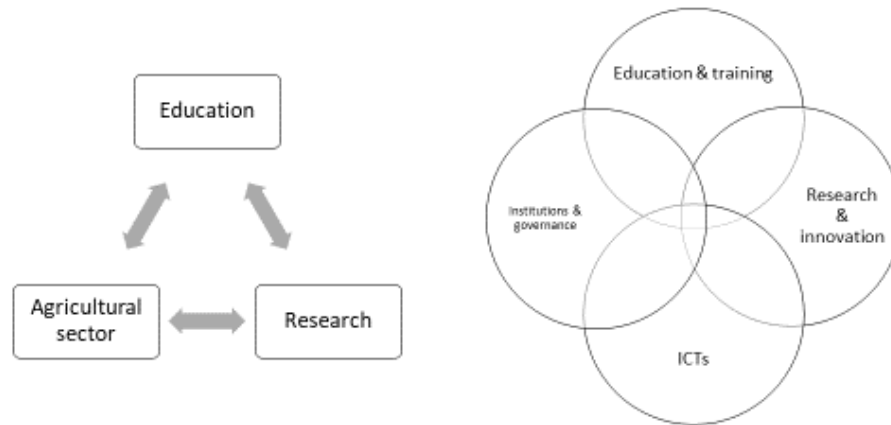
(AKIS) underlines that innovation is a social process, more bottom-up or interactive than top-down from science to implementation. Even pure technical innovations are socially embedded in a process with clients, advisors etc. Very often partners are needed to implement an innovation; Intermediate actors such as farm advisors and innovation brokers may play an important facilitating role in bridging between science and practice, and between specific in-depth knowledge and a holistic entrepreneurial approach. The focus is on bottom-up approaches and cooperation between farmers, advisors, researchers, businesses and other actors in operational groups to realise innovations. It is expected that this knowledge "exchange" will generate new insights and ideas and mould existing tacit knowledge into focused solutions.

Social Innovation : Innovation is a broad concept. The OECD defines innovation as the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations (OECD and Eurostat, 2005) This implies that innovation activities are all scientific, technological, organisational, financial and commercial steps which actually, or are intended to lead to the implementation of innovations. And there is social innovation, a term that not only refers to the social aspects of innovation, but also to innovations in social life. Innovation starts with mobilising existing knowledge. Innovation for rural development attracted a great deal of interest in the literature. Several models were put forward starting from linear models to more systemic ones (Knickel et al. 2009) where innovation is seen more as a collaborative process, where learning happens between the various stakeholders (Moseley 2000, Pouch 2015). The emphasis is put on the diffusion and the capacity of innovation and clustering of the rural population (Morshedi & Lashgarara 2011, Cooke & Harts 2007, Florida, 1995). In rural areas *social innovation* is seen as a key element : It can be defined as social interactions to meet one or more common goals , new or improved ways of collaborative actions (Mumford 2002, Neumeier 2012) and constitute one of the pillars of sustainable rural development processes (Dargan and Shucksmith 2008).

The transition to an innovation-driven knowledge economy can lead to increased productivity, higher living standards, and improved competitiveness in the global market. By harnessing the power of knowledge and innovation,

countries and regions can adapt to changing economic landscapes and foster sustainable growth.

Figure 1: The S&T-KBE model used in the Rural Renewal Policy



2.2.3. The application of the IKBE model in rural development in algeria

For rural development, territory is central. A territory is not only spaces that demand resources from elsewhere, typically from the State, but also a concentration of latent resources of knowledge, experience, knowledge, and know-how. It is a concentration of territorial intelligence that needs to be understood, grasped, and mobilized for the benefit of territorial development. The explosion of the concept of territorial intelligence in literature, particularly among economists and geographers, is not a coincidence. It is because previously unsuspected resources, both intellectual and material, have been discovered within territories. In the following chapters of the second part, we will see how this is concretely reflected in the agricultural and rural development model adopted by Algeria. The new paradigm seemed particularly suited for rural areas (Conteh 2012) where knowledge production, dissemination and utilization can be facilitated through knowledge networks at the local level.

The interest shown by Algeria in the KBE paradigm started in 2002 under the impulsion the World Bank Institute for the MENA region⁶ which led to the first National Conference in KBE⁷ in 2006 by the Minister of Agricultural and Rural Development and the creation in 2007 of the KBE ad-hoc committee⁸ by the National Economic and Social Council⁹ (Djefflat 2006). Consequently the MADR was at the forefront and decided to format the whole strategy for rural and agricultural development using a KBE approach a new paradigm shift for a new rural policy (Clamour 2018, Aubert & Reiffers 2014) playing thus a pioneering role. We will examine in the next section how the Rural Renewal

Policy (RRP) and its main flagship programme the PPDR as main policy instrument which largely benefited from the IKBE approach.

The Algerian IKBE draws its roots from the science and technology policy (S&T) policy (Oukil 2014) adopted in the early 80s but through the narrow lens of higher education. The main objective was to supply the necessary competences needed by the productive sector¹⁰ (Beddek 1993, Djeflat 2010). The turning point was the promulgation of the 1998 law on scientific research and technological development¹¹ encouraged the public as well as the private sector to invest in R&D and created a dedicated national research fund (FNR)¹² with the aim to allocate 1% of GDP to research by 2002. The new law was extended to the agricultural and rural sector. This period saw also the birth of the KBE policy adopted subsequently in the hope to accelerate innovation and knowledge driven inclusive development. But it was until 2003, that local authorities saw some kind of interest in the innovation as a necessity for the stagnant industrial sector.

III - The proximity programme for integrated rural development (PPDR) and the IKBE policy.

3.1. The foundation and implementation of the new policy and programme

The new policy initiated in 2000¹³ by the Algerian Government was to turn to its agricultural and rural sector, largely neglected before, as a new engine of growth on top of the mineral sector. It was an attempt to achieve a more diversified economy through the rehabilitation of the agricultural and the rural sector which employed about 14% of total active population (Lebeche 2011) and reduce food dependency (Rastoin and Benabderrazik 2014). The development of agriculture is a response to the challenge of food security, which is an integral part of national security.

The idea of building an agricultural and rural economy that maximizes knowledge emerged was born in fact from a large National Consultation held in 1992 to assess the progress made by the sector: The main objective of the consultation was to conduct « an unbiased diagnosis » of the state of agriculture after thirty (30) years of independence and to propose a new approach to the development of the agricultural and rural economy (Benaissa 2021). The consultation also addressed other topics related to scientific research, agricultural extension, technical support to production, its factors, technical itineraries, agricultural hydraulics, and heritage protection.

The Agricultural and Rural Renewal Policy (ARRP)¹⁴ initiated in 2009 constituted a major innovative policy chosen for rural and agricultural development, (MADR 2016). It was also the end of the centralized top-down mode of governance of rural territories and the need to implement a more integrated, participatory and inclusive development that gives farmers the opportunity of learning from each other through a new mode of governance

based on a re-centering of the State's role on its regulatory functions, a profound change in the relationships between actors in the agricultural and rural world, and the gradual construction of a genuine public-private partnership (Chapman and Slaymaker, 2002, Bendjeffal and Benabdelli 2016,). It was perceived by the Ministry as a paradigm shift or a new rural policy, thus playing a pioneering rôle (Benaissa 2021). The new paradigm appeared particularly well-suited to rural areas where the production, dissemination, and utilization of knowledge can be facilitated through local knowledge networks.

The Rural Renewal Policy (RRP) on which we are focusing our attention has three main tools dedicated to rural renewal: The "National Decision Support System for Rural Development (SNADDR)¹⁵. The "Information System of the Rural Renewal Support Program (SI PSRR)¹⁶ and the Proximité Program for integrated rural Development (PPDRI)¹⁷. In addition, the Human Capacity Building and Technical Support for Producers (HCBTS) named in french PRCHAT¹⁸ is common to both the ARP and the RRP. It was launched by the MADR in 2010¹⁹. It included in particular 1/ a greater investment in research and training to facilitate the development and transfer of new technologies , 3/ the strengthening of human capacities of all the institutions and bodies responsible for the support of farmers and operators (MADR 2010). It benefited from an annual budget of 24 billion dinars (197 million euros) in the 2010-2014 period

The ARRPP used primarily logframe (logical framework methodology) to implement its various programs (MADR 2010). In our specific case, the logical framework is structured around a pressing call for mobilization, understanding, knowledge, and the utilization of new information and communication technologies (ICT), as well as innovation in all fields and at all levels (central, intermediate, local, and sub-local) (Benaissa 2021b). The Logframe was therefore a unique learning opportunity and a major innovation in the eyes of farmers and all keyplayers at various levels. It was also a living lab experiment before term defined as a "real-world settings" in which occurs "co-creation" between scientists, public decision makers, private sector and citizens that work with each other in a new way (Toffolini et al. 2021). It is now an ultimate instrument of knowledge based innovation. The logframe learning process took place over a period of thirteen years (from 1992 to 2013). It was developed incrementally in terms of its content, with a continuous search for the best means to mobilize as many people as possible around shared objectives (Benaissa 2021b).

We will not look in any depth at the ARP in this contribution. The RRP was built primarily on the basis of *"an innovative approach to rural development which targeted primarily areas where production and living conditions were most difficult for farmers (mountains, steppe, Sahara)"* (MADR 2016) based on the voluntarist attitude of the State to use a more participative and inclusive approach.

We will concentrate in the next section on the Proximity Program for Integrated Rural Development (PPDRI²⁰) which was the main policy instrument to implement the RPP.

3.2. The PPDRI

The PPDRI²¹ was part of sustainable rural development strategy (SNADDR)²² used to implement the RRP. The PPDRI was intended to assist rural populations in consolidating their basic economic activities and expanding to other innovative productive ones through participation and inclusiveness. Four main areas are covered a/ Modernization and rehabilitation of the villages and ksours¹ and improvement of the quality and the conditions of life in rural areas; b/ Diversification of economic activities c/ Protection and valorisation of natural resources; and d/ Protection and enhancement of the rural intangible heritage.

3.2.1. The participatory dimension: The participatory approach is one of the fundamental elements and guiding principles that have shaped the construction of the Agricultural and Rural Renewal policy. The involvement of all stakeholders was sought through effective, responsible, and interactive participation. It was based on the belief that the success of rural development projects depended to a large extent on the active and intense participation of rural populations (Meister 1969, Chambers 1995), a change in attitude of the authorities explained by the failure of non participatory programmes conducted in the past (Chaib 2015). Participation was, thus, the backbone of the PPDRI and through this new programme, public intervention became *"horizontal, proximity, bottom up, integrated, participatory and decentralized"* (Souidi & Bessaoud, 2011; Chaib & Baroudi, 2014) at territorial level (Enda Graf Sahel, 1993) based on proximity rural development which can take several forms (Murdoch 2000, Maiga 1984) and can be run by the local development State²³ (Bocher 2008). Farmers can generally participate through their associations (nearly 1300 associations created since 1999) (Bessaoud 2008). Several problems were solved this way: access to land, difficulty of reimbursement of Bank loans etc. However, the participation of farmers took a new turn through the new institutional architecture created at the local level and which will be examined later.

3.2.2. The inclusiveness dimension: aims at reducing inequalities, combating social exclusions (Larose 2016) and ensuring that all marginalized and excluded groups become stakeholders of the development processes (Pouw and Gupta 2017, Usman 2013). Inclusive rural transformation is thus a critical component of sustainable development (IFAD 2016) and raises the issue of the participation of Rural women in the PPDRI. Women are known to be a key player in rural areas and the pillar of rural households (Palmer 1980, Ogunlela and Mukhtar 2009). Women empowerment has shown a decisive impact on rural development and its sustainability (Palmer 1980, Ogunlela and Mukhtar

2009). In principle, the PPDRI did not discriminate against women and they can fully participate in all components of the PPDRI.

3.2.3. PPDRI implementation: the achievements of PPDRIs seem impressive according to the official assessment (MADR 2015): 10 842 PPDRIs were launched and 6468 completed (60%) during the period (2009-2014). They cover 1400 communes and 10 000 rural localities involving 1.1 million households representing 18% of the total population. By theme, the PPDRIs on valorization of natural resources, came first (50% of the projects launched) followed by diversifying economic activities (37%), the modernization and / or rehabilitation of villages (10%) and finally the protection and enhancement of the tangible and intangible rural heritage (03%). The programme benefited from 600 billion Algerian dinars (DZD)²⁴ (more than five billion US Dollars). This relatively successful picture needed to be confronted to the reality through the eyes of the analysts and the main beneficiaries, namely the rural population and farmers. This will be done in the empirical section. We will examine in the next section the links between the IKBE policy and the PPDRI.

3.3. The IKBE components of the PPDRI

The PPDRI had several elements which indicated the willingness of the authorities to modernise rural area through and a IKBE approach. We will examine below the four components of this strategy: innovation, training learning, ICT and institutions which are also the four pillars of the basic KBE model seen earlier. For lack of space, the research component will not be examined here.

3.3.1. Innovation

Five categories of innovations seem to have taken place in the PPDRI (table 1). Firstly, the PPDRI promoted various technical innovation various activities: in pottery, in cloth making, in product conservation and in management of local heritage. Secondly, Government introduced a new territorial governance system (decentralisation, new tools of decision making and information gathering) to enhance participation of key players at the rural territory. Thirdly, several mechanisms related to the financial sphere were introduced and which we will look at them in more details later. Fourthly, new instruments related to the sphere of information were introduced and fifthly new actors who play a key role were mobilised.

Table 1 - Social and technical Innovative processes introduced by the DS at rural community level

New organizing	New Financing	New Information systems	New Actors
awareness raising	support funding	Information flow using databases	Facilitators
decision-making	microfinance	decentralized geographic information systems (GIS)	Animator
programmement	risk management	Communication system	Networks of actors
management	Proximity financial		Project leaders
monitoring	Community interest free finances: rfig		Associations representatives
institutional strengthening	Leasing of equipment		
facilitation	Insurance scheme		
Cooperation between actors			

Source: the author

This contributed to the revival of certain sectors in agro-food, and in the mechanical and agro-chemical industry, etc. and the creation of over 240,000 full time-equivalent permanent job during the << 2009 for example.

3.3.2. The learning and capacity building process

This is a determinant aspect for the success of the rural renewal and an important component of the IKBE model. The new philosophy was to find new ways for competence-building for a more effective participation of rural population. This was done through the PRCHAT.

3.3.3. ICT usage:

ICTs have a great potential to promote rural development through access to information, and increased decision-making capacity (Chapman and Slaymaker, 2002) and higher participation, empowerment and inclusion of rural population (Richardson and Paisley, 1998). In addition, they can help local e-administration. shows that there is a great potential for using existing social software tools and platforms for communication, interaction, knowledge sharing, preservation of information in the agricultural sector and, as such, stimulate multi-actor innovation (Jespersen et al., 2013) The analysis has identified some important barriers which need to be overcome to obtain the full potential of the use of social media and other ICT tools in the agricultural

sector. The conclusion is that (online) communities exist that can disseminate expert knowledge to other researchers and practitioners. This has the potential to lead to more collaboration between researchers and practitioners;

Both were developed by the BNEDDER which is a consultancy office under the authority of the MADR²⁵ and aimed at an alignment of the local system with international practices (Parker 2000).

3.3.4. Institutions

The effectiveness of the State rests also on its capacity to manage rural transformation through adequate functioning of the institutions in charge of the implementation of the State policy (Böcher 2008, Fox 1995). Both top down and bottom up approaches are needed giving the opportunity of local communities to fully participate (Goldenberg 2008, Conteh 2012). The implementation of the PPDRI needed new institutions and actors described below.

-Three levels of institutions a/ *The rural municipality animation cell (CMAR)* at the lowest level which is in direct contact with the rural communities. It has also a broad representation of major stakeholders²⁶. b/

*The technical committee of the Daira*²⁷) (CTD) which constitutes an important body where all technical services and specialists are present including the Rural Development Bank. c/ *The Willaya Technical Committee (WTC*²⁸): The willaya²⁹ (prefecture) is the highest decision-making institution, and a representative of Government at the regional level. It deals with all matters related to the PPRDI at willaya level (MADR 2015).

The Project team: included the *facilitator* appointed by the RMAC who liaises between the population and the administration and the *animator* designated amongst the local community and who become de facto project leaders. Together with local associations, they activate in the *Rural Animation Cell* (MADR 2009) through intense participation (Meister 1969).

IV- Case-study analysis

Rural development driven by IKBE requires a variety of actions to be conducted simultaneously by the State for an effective structural transformation of rural areas³⁰ (Parker 2000, Grimes 2003, GIFAD 2016).

The five case studies we have selected from the literature have examined in depth the issue of participation of the rural population and the farmers to the PPDRI (Akerkar, 2015). They were amongst the first to benefit from the PPDRI. They were drawn from three of the most important regions of the country: three from the West : the Willaya of Tlemcen³¹ (Hattab & Gaouar 2016), the willaya of Ain Temouchent (Chaib 2015)³² and the willaya of Mascara³³ (Bendjeffal and Benabdelli 2016), one from the center , the willaya of

Bejaia³⁴ (Akerkar 2015) and one from the East: the Willaya of Sétif³⁵ (Zaghib 2009). The extensive field investigation included key players (farmers, facilitators, animators, project leaders and representatives of local authorities) and used questionnaires, discussion guides and focus group. A total of 524 people were interviewed and constitute our sample (Table 2).

Table 2: Structure of the sample surveyed in the five case studies

Region	Field work instruments	Size of the sample (key players)	Rural localities
Tlemcen (North-west°)	Structured questionnaire+ focus group	122	Ain Fezza, El Gor and Sidi Djilali)
Sétif (North-East)	Questionnaire	158	Iaoutiouene, bouimene(aït tizi)
Ain Temouchent North-Ouest		40 (estimated)	
Mascara West	Questionnaire plus focus groups	40	Municipalities of Hachem, Zalamta and Nesmoth
Bejaia Centre	Questionnaire plus focus groups	164	
Total		524	

Our contribution is to look at them through the lenses of IKBI. It was not an easy task to have the same volume, depth and quality of the data and this is one of the limits of our work. The emphasis was on PRR (rural), we have also included one case from PRRA (Agriculture). We used the IKBE framework with its four main pillars (Innovation, Training, ICTs and Institutions) to which we have added participation/inclusion as another pillar to adapt to the rural world (Fig. 3). This is our contribution to the conceptual framework. The new framework translates into six pillars: Innovation (including financing), capacity building (PRACHT), ICT (SI-PSSRR), Governance and Institutions (DSSSD) , and Participation/inclusion and will be used as an analytical tool of the reality of the field.

4.1. Innovation:

The achievements vary from one willaya to the other. We have three situations in our cases. The first one is considered relatively successful: in Tlemcen and

Ain-Temouchent, the PPDRIs embraced large sections of rural activities (*Land improvement, Fruit plantations projects and Hydro-agricultural projects*). Many farmers have shown a great interest to expand their agricultural land to overcome the obstacle of fragmentation in small sizes and which prevent them to reach high productivity (Jia & Petrick, 2013). They have shown dynamic attitude in introducing rustic fruit species such as olives in dry land, almonds and figs and new fruit trees such as cherry trees. They thus contributed to crop diversification, and the creation a totally new market locally (Hattab and Gaouar, 2016). Finally, the acquisition of new hydro-equipment and the renewal of the existing one allowed farmer to increase the depth of their drillings and raise water flows. However, some farmers showed a certain 'resistance to change'. Same success in the adoption of new techniques was registered in the case of Mascara where the first year (2009) saw the start of 96% of projects in the modernization of the villages for improvement of the standard of living of households, 76% in diversification of economic activity and 87% in the protection and enhancement of naturel resources.

In the second category (Sétif), the PPDRIs included the construction of basic socio- economic equipment (health center, road and rural housing) for the improvement of the living conditions, the introduction of new equipment (hydropower pumps and for the protection against floods) and micro-finance projects. Three years later, only three projects seem to have been completed while the rest were either underway or abandoned. Many projects suffered the poor quality of infrastructure (the tracks, the works of art, the basins, the torrential corrections, etc.) and a relatively strong resistance on the part of rural population.

In the third category of cases, innovative projects met some difficulties. Thus in Béjaia, the rate of implementation of PPDRIs was relatively low in the first year: 11% of the PPDRIs were implemented covering 8% of households and 16% of the localities, however 15% of the actions only were for rural development, the rest was for agriculture. Only 57% of the funds for the year, were used and, projects related to the diversification of economic activities such as tourism, handicrafts and local products with creative contents were insignificant. According to the population, the authorities in charge seem to have privileged physical achievements through quick project rather than those which contribute to structural transformation.

Financial innovation: New 'proximity financing' mechanisms were introduced, through the launching of a new instrument, the RFIG³⁶ which is a "no-interest" credit and can be considered as one of the major innovation in micro-finance, the strengthening of the leasing credit for the purchase of agricultural equipment, and new insurance systems (Laib & Chakour 2018). A new multiple-sourcing mode of financing was introduced with funds coming from the rural development fund for land reclamation (FDRMVTC)³⁷, from the communal rural development plans (CRDP)³⁸, from the traditional communal

Development Plans (CDP) and from private sources (bank credit, public subsidy and self-financing) (MADR, 2012). All this was accompanied by a new legislative and regulatory framework. We have here again different situations. In the first category, the case of Tlemcen and Ain-Temouchent, public funding was channelled through the FDRMVTC and to a lesser extent the PCD-DR and the PCDs. Private funding came through bank loans and self-financing. This model proved to be, however, difficult to implement in poor mountainous areas. Poor farmers found it difficult to bank credit subjected to guarantee, and to provide self-financing (MADR, 2008).

In the second situation, in Mascara, the tendency was to rely excessively on State budget channelled through the Bank of Agriculture and Rural Development (BADR), a public bank, in the form of micro finance. And in some poor mountainous rural areas, personal contribution did not seem adequate, as farmers in poor areas did not have the necessary self-financing capacity.

In the third situation, in Sétif micro-credits from the bank seems to have missed their targets as indicated by the rural population and did not correspond to their needs. In the fourth situation, in Béjaia, the breakdown of sectoral financing shows that agriculture accounts for almost half of the total programme credits (47.7%) followed by the improvement of living conditions (43.4%) hydraulics (1.4%) and, fishing and forests (0.7%). This imbalance in funding has resulted in imbalances in physical achievements. The difficulty of mobilizing the different sources of financing resulted in a pronounced over spending of the resources of the FDRMVTC and to a lesser extent those of the PCD-DR and the PCDs. In addition, the amount of public subsidy seemed a little incentive for beneficiaries of PPDRIs in the absence of the readjustment of funding according to the particularities of mountain areas which are poor and deprived. Moreover, farmers, see it as a mere distribution of funds by the State, the logic of the rentier culture (Bizri 2013) and another way to finance agriculture at the expenses of rural development. This raises the issue of capacity of the DS to find the right balance between public and private funding in promoting rural development.

4.2. Training and competence building

In order to build human capabilities, the PRCHAT was implemented in all five PPDRIs with various levels of success. In both Tlemcen and Ain Temouchent, the programme met a relatively good acceptance and a successful implementation as a result of the attention paid by the local administration to the needs of local farmers and their capacity to adapt. In Mascara, it was implemented satisfactorily in its training components according to the participants. However some shortcomings were recorded mainly the insufficient qualification of trainers from urban areas, not knowing rural reality. In Sétif, farmers and the rural community who saw no benefits in it, probably due to bad implementation. In the case of Béjaia, the programme

seems to have arrived too late in the eyes of the population, in addition to qualitative and quantitative deficits in human resources and material means. This raises the important question of the timing of training and the celerity of implementation in addition to the choice of pedagogical methods bearing in mind that the rate of illiteracy of 26%³⁹ is still relatively high among rural population.

4.3. ICTs :

ICTs played a key role in the PPDRI mostly through the SI-PSSR. Four facilities were provided by the system all performed online 1/ the "PPDRI assembly and design" for rural farmers and key players to undertake editing functions such as registration of their projects, confirmation, validation, and approval 2/ the "*monitoring of the achievements of the PPDRI*" for farmers to follow the level of projects realization 3/ the "*access to the PPDRI Support Programme*" at the Willaya and the Daira level to all projects registered and 4/ the "*degree of completion of support structure*" which indicates to what degree the procedure of PPDRI is completed. By 2008, the SI-PSSR, had been used by 26 willayas out of 48 ie: 54% (PM 2008). To date most willayas seems to have used it.

4.4. Institutions

Several aspects have come out from the empirical studies. While the institutional dimension of the PPDRI has made a remarkable progress, there were many difficulties reported in the field studies. Firstly, the PPDRI suffered a lack of coordination between the different central decision-making bodies such as the Ministry Departments and locally (Ain-Temouchent) as a result sometimes from the lack of cooperation among local administrations. Secondly, the bureaucratic top down approach adopted procedures undermined the sense of appropriation of the programme by the population in certain Willayas (Béjaia.). Thus, rural population saw it as another hierarchical intervention of public authorities (Sétif) in the face of red tape and absence of transparency. Thirdly, the bad diagnosis of the needs and aspirations of rural communities done by the local administration seems to have led to inadequate solutions of rural populations. In this respect, the facilitators actions to overcome misinterpretations were not been very effective, and the rural population perceived the PPDRI as yet another "intellectual production exposed skilfully". Finally, the Directorate General of forests responsible for the implementation of PPDRI, according to analysts had no qualifications to manage the participatory and bottom-up character of this programme.

4.5. Participation and inclusiveness

4.5.1. Participation: The level of participation was measured by the level of attendance to meetings at various levels. *At the rural municipality animation cells* (RMAC) participation was relatively high in both Tlemcen and Aint Temoucent. The two places could mobilise most key players and stakeholders

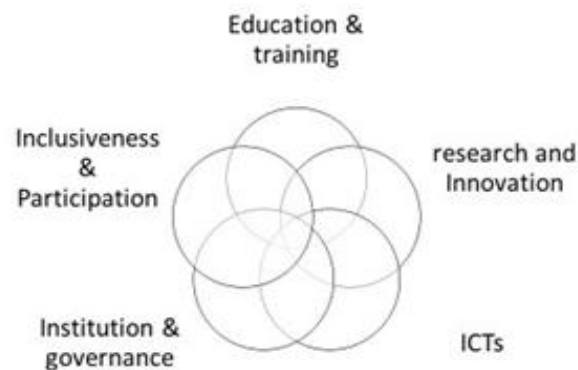
including the local university which was a novelty bearing in mind this participation did not exceed 4% in the RMACs of the country. But certain rural municipalities registered only minor participation, sign of some problems experienced by rural farmers. In Mascara, low attendance was registered which may mean low level of awareness of the importance of these meetings , lack of appropriation of the programme by local rural population and the feeling that their aspirations were not taken care of properly. In Sétif and Béjaia, very little participation was registered at meetings at different levels, the project being seen as imposed by local administration and not reflecting their true needs.

4.5.2. Inclusiveness: is examined essentially through women participation. Women who had low level of literacy but practical experience only met difficulties in benefiting from the training programme and seem to be largely under-represented in the various structures: for example, no woman was amongst the animators or facilitators⁴⁰. This situation poorly taken into account by the designers of the programme led to very low level of inclusiveness. Amongst the obstacle mentioned, some traditions of the region seem to have been played a role (eg: inhibitions regarding transactions and negotiations with men locally).

5. Discussion and concluding remarks

Our four initial questions seem to have had adequate answers through the analysis. Regarding the first question, the results show that the PRR and in particular its flagship programme the PPDR have been effectively formatted on the basis of KBE policy, initially by the 1998 law on STI and subsequently by the new KBE paradigm adopted by the MADR. Four important policy instruments linked STI- KBE and PPDR : the IS-PSSR (ICT), the RFIG (finance), the DSSD (Governance) and the PRCHAT (training). This way, the PPDR became grounded on the four pillars of the KBE model to which we added participation and inclusiveness increasing the prospects of rural transformative (Figure 3).

Figure 3 : The five pillars STI-KBE model for inclusive and participatory rural development

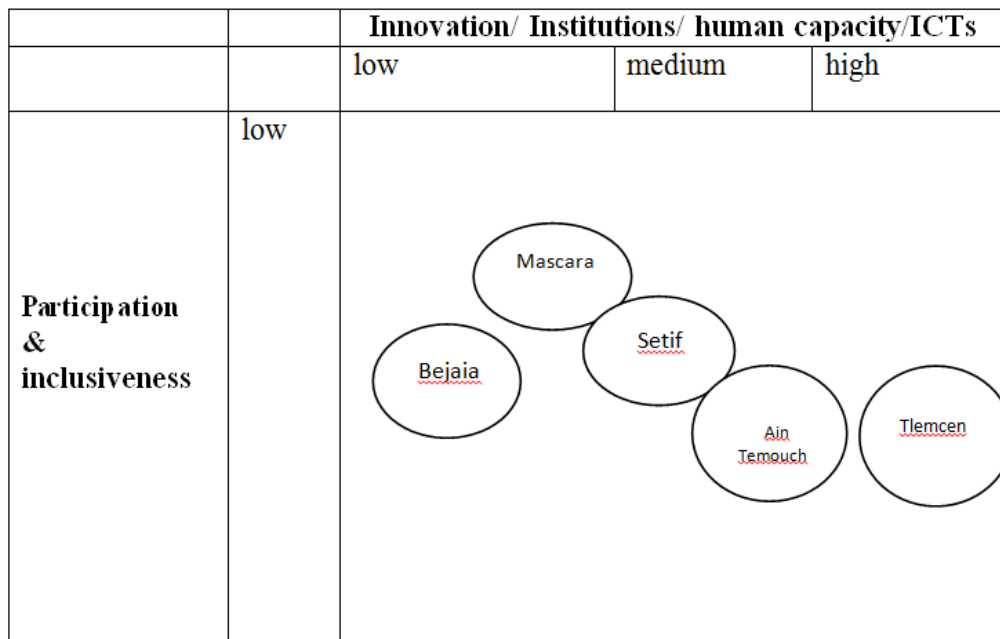


Regarding the second question our analysis indicates that the DS voluntarist policy was reflected through the key role played by the MADR in impulsing an explicit strategy centered around STI and KBE. The State played a key role through the 1998 STI law which was extended to agricultural and rural development and the deliberate adoption of the IKBE model. This was reinforced by the a very proactive and innovative attitude it adopted and the introduction of various new policy instruments. Similarly, the State adopted decentralised decision-making mechanism and new modes of governance to enhance participation and inclusiveness.

The third question and participation and exclusiveness was answered through the empirical work and the case studies we examined. It is clear that the new ambitious PPDRI programme for rural transformation needed an intense participation of rural population away from the old traditional top-down bureaucratic procedures. The results show that the level of participation is not yet fully accomplished, and the decentralization of decision remains unfinished. The level of participation and inclusiveness depended on the capacity of the local governance system in creating the right ecosystem where IKBE based projects could develop successfully. Our results indicate that the approach succeeded in some places and failed in some others. Three categories of situations prevailed: the first one indicates a low level of integration in the IKBE eco-system leading to low participation and inclusiveness. The second one indicates a medium level of participation and inclusiveness resulting from partial integration into the IKBE eco-system. The third situation indicated a relatively high level of participation resulting from a pronounced implementation of the IKBE model. Nonetheless, inclusiveness of women remains weak in all three situations. Further research is needed to clarify the roots of this distribution, but it is clear that the geographical, socio-economic

and political factors were at play. In particular, the municipalities posture and attitude towards the PPDR and the perceptions and attitudes of the rural population have played a decisive role. Using these we could map the different willayas on a grid combining IKBE and participation inclusiveness (Figure 4).

Figure 4: Mapping the different willayas in the STI-KBE grid



Source: the author

The fourth question on the obstacles met is probably the most addressed one in the studies selected here and the literature on the PPPRI in general. It is clear that the programme let to tangible results and satisfaction in some rural areas while causing frustration and discontent in others as a result of the several obstacles met. First of all, the 1998 law on STI did not quite impulse the level of innovation required by the structural transformation required. Secondly, the PRCHAT seems to have missed its targets in many rural areas following difficulties in implementation and misinterpretations by the populations. This is on top of difficulties in establishing fruitful links with the academic world and the lack of recognition of the importance of the accumulated tacit knowledge through learning by doing of farmers rural population. Thirdly, the study show that the implementation of the programme suffered coordination problems at the highest decision making level as well as locally, missing the opportunity to establish a real Rural Innovation System. Fourthly, the implementation of the IKBE met important obstacles related to resistance to change in some areas probably minimized by the designer of the programme itself. The implementation failed to create the right IKBE eco- system needed which translated in low participation to the various committees of rural populations in addition to low inclusion of women. It also contributed to forge

the attitude of rejection seen in some areas. The PRR, as a whole and the PPDR in particular suffered, no doubt, from the negative heritage and image of previous plans and programmes decided centrally by the State and which failed.

To conclude, while the PRR is completing its first decade of life, new conditions have to be taken into account: the financing model based on rent is not possible anymore in view of the falling oil prices and income. There is therefore hence the need to readjust the economic model used so far, where private financing through the private banking system and private financing take over with selective support to poor mountainous areas. The IKBA model which has been relatively successfully integrated into the PRR and the PPDR in particular cannot be sustainable unless the sphere of knowledge and the university in particular is massively involved in pursuing and deepening the design and implementation of this programme and the country as a whole opts for a KBE model. Hence the need for even more profound action of the Development State.

Acknowledgements: I am indebted to several colleagues who helped with data collection and insights namely to Mr. Rachid Benaissa, former Minister of Agriculture and Rural Development of Algeria

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Notes

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- ¹ RRA stands for Renouveau Rural et Agricole: the french version of the acronym is kept throughout the text for ease of research
 - ² PPDRI which stands for Programmeme de Proximité pour le développement rural intégré.
 - ³ President Boumédiène, the second President of Algeria (1965-1979)
 - ⁴ Selected industries included steel, metallurgy, the mechanical, the electrical and electronic sectors)
 - ⁵ SCAR means Standing Committee on Agricultural Research,
 - ⁶ MAGHTECH stands for Maghreb Technology the first and largest network activating in the field of technology for development created in 1994: Maghtech.org
 - ⁷ The Maghtech Network in partnership with the Algerian Association for Technology Transfer) played a key role in advocacy work leading to the organization of the first KBE national conference
 - ⁸ The author was member and advisor of this committee
 - ⁹ Conseil National Economic and Social (CNES) in French
 - ¹⁰ For many years, R&D expenses did not exceed 0.3% of GDP .
 - ¹¹ Law n° 98-11 called 'law of orientation and Programme for the development of scientific research and technological development 1998-2002
 - ¹² Fonds National de la Recherche in French (FNR)
 - ¹³ With the newly elected President Bouteflika
 - ¹⁴ PRRA : Politique de Renouveau Agricole et Rural
 - ¹⁵ Système National d'Aide à la Décision pour le Développement Rural
 - ¹⁶ Stands for « Système National d'Aide à la Décision pour le Développement Rural »
 - ¹⁷ Stands for Projets de Proximité de Développement Rural Intégré
 - ¹⁸ PRCHAT stands for Programme de Renforcement des Capacités Humaines et d'Assistance Technique
 - ¹⁹ Programme de Renforcement des capacités humaines et d'assistance technique
 - ²⁰ PPDRI stands for
 - ²¹ Programmeme de Proximité pour le Développement Rural intégré (PPDRI)
 - ²² SNADDR stands for Stratégie Nationale pour le Développement Durable Rurale.
 - ²³ The overseas development institute – London - UK
 - ²⁴ 1 USD = 118,77 DZD (algerian Dinars)
 - ²⁵ BNEDDER stands for Bureau National d'Etudes pour le Développement Rural
 - ²⁶ ANSEJ (Youth employment Agency), CNAC (National Chamber of Commerce)
 - ²⁷ Comité Technique de Daira (CTD)
 - ²⁸ Comité Technique de Willaya (CTW)
 - ²⁹ There are forty-eight willayas in the country
 - ³⁰ Taken from the call for papers of this special issue
 - ³¹ located at 600 km of the capital Algiers is close the border with Morocco.
 - ³² located in Western Algeria 500km West of Algiers.
 - ³³ Located about 400 km west of the capital,
 - ³⁴ located at 220 km East of Algiers
 - ³⁵ located in the East of the country at 300 km East of Algiers.
 - ³⁶ Taken from the rural colloquial Arabic, Rfig means the companion, the person we can trust and on whom we can rely
 - ³⁷ FDRMVTC stands for Fonds de développement rural et de la mise en valeur des terres par la concession (FDRMVTC)
 - ³⁸ PCD-DR : stands for Plan de Développement Communal Rural
 - ³⁹ National Office of Statistics
 - ⁴⁰ Rural woman is not supposed to talk to strangers (to the locality)

Absorptive capacities and connectivity capacities: The evolution of Latin American Innovation Systems (1970-2017)

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Introduction

Development studies from Latin America have widely discussed the relevance of the national capabilities to produce and exchange knowledge to achieve productive and social developmental goals (e.g. Sagasti, 2005; Sabato and Botana, 2021). Relatedly, since the last decades of the 20th century, the concept of innovation system (IS) and, in particular, the national innovation system approach have been integrated, with criticism, in the developmental studies in Latin America (Chudnovsky, 1999; Arocena and Sutz, 2000a; Chaves *et al.*, 2020).

Studies from Latin America have characterized Latin American ISs as incomplete or immature (Arocena and Sutz, 2000a; Rapini *et al.*, 2009) and stressed the weakness of external connectivity and absorptive capacities in the region (Erbes *et al.*, 2010; Yoguel and Robert, 2010; Arocena and Sutz, 2010; Dutrénit and Puchet, 2011). Moreover, other works have emphasized that the peripheral position of Latin American ISs shapes both their participation in the global IS and the local dynamic of knowledge production and appropriation (Albuquerque, 2007; Chavez *et al.*, 2020).

Previous research has advanced understanding of the evolution of the Latin American ISs at the level of individual countries or groups of countries, mostly based on in-depth national case studies (e.g. Cassiolato *et al.*, 2003; Dutrénit *et al.*, 2010). However, comprehensive longitudinal studies based on standardized data for the entire region are scarce (Castellacci and Natera, 2016; Confraria and Vargas, 2019). In addition, prior works have claimed that, to advance understanding of underdevelopment beyond the study of catching-up processes, the IS approach requires a theoretical basis to analyse the emergent

properties which arise from the systemic interactions rather than simply identify the institutional setting or the evolution of innovation investment (Arocena and Sutz, 2000a; Yoguel and Robert, 2010).

Following the complex systems approach (Yoguel and Robert, 2010; Antonelli, 2017), in this paper we contribute to the understanding of the evolutionary paths of Latin American ISs by defining and measuring their absorptive and connectivity capacities. The concept of absorptive capacities was early coined in management studies (Cohen and Levinthal, 1989 and 1990) and subsequently applied in studies of innovation and development at the national level (Castellacci and Natera, 2016; Filippetti et al., 2017). Both, at the firm-level and at the national level, it refers to the collective ability to recognize, understand and integrate new knowledge into problem-solving activities. This ability refers to a sort of cumulative repository of capabilities (Fagerberg and Srholec, 2017), a systemic attribute, that is greater than and different from the mere sum of the system's components. External connectivity capacities, meanwhile, are a systemic attribute associated with one of the central challenges identified by development studies: the ability to access and participate in varied knowledge flows. These IS attributes are intrinsically intertwined because positive feedback between them is a necessary condition for the evolution of an IS (Erbes et al. 2010; Yoguel and Robert, 2010; Chaves *et al.*, 2020).

Since these system attributes are non-directly observable phenomena, to address them it is necessary to build systemic measures based on the interactions between the systems' components (Britto et al., 2021; Balland et al., 2022). We observe these interactions by using data from the US Patent & Trademark Office (USPTO) in order to build and analyse collaboration networks connecting inventors and patent owners in all Latin American countries during a 48-year period. Applying social network analysis techniques, we study, on the one hand, national networks' internal cohesion as an indicator of the absorptive capacities in a given IS. On the other hand, we analyse external connectivity capacities in terms of the degree of openness maintained by the national network through connections with other countries.

By studying these two IS properties, this paper provides a novel comparative analysis of national capacity accumulation and offers empirically grounded explanations that complement and enrich extant knowledge concerning Latin American ISs. Our findings illustrate that both absorptive and connectivity capacities in Latin American ISs have increased, exhibiting, in most cases, a positive relationship between the two capacities. We identify different trajectories among Latin American ISs according to the co-evolution of these systemic attributes and according to structural features of the national ISs. However, as a general pattern, we observe that collaboration networks are mostly fragmented and outward- oriented.

2. Systemic disconnections in Latin-American ISs

Innovation has been defined as an uncertain and cumulative problem-solving process that is interactive in nature. According to this view, solving complex problems requires a wide variety of knowledge distributed among a broad set of actors, and innovative solutions emerge from the interactions of different agents acting under uncertainty due to incomplete information and partial understanding of the environment (Dosi, 1988; Lundvall, 1988). The complexity approach similarly defines innovation as an emergent property of the ISs, which results from micro-level interactions among agents in the IS (Antonelli, 2017; Balland *et al.*, 2022). This creates feedback loops between the system's building blocks, which determine how the IS evolves.

The (under)development path of Latin America has been associated to the inability to overcome structural disconnections within the national ISs that operate between different subsystems, hindering learning processes. Building on the pioneering ideas of Furtado (1964), authors in this line of inquiry have proposed theoretical interpretations of underdevelopment, a situation they view as qualitatively different from development and associated to a differentiated systemic evolution compared to developed countries (Arocena and Sutz, 2000a; Cimoli and Porcile, 2009; Yoguel and Robert, 2010).

Trajectories of underdevelopment, has been associated to uneven paths signed by the inability to overcome structural restrictions to development, including the production and use of knowledge. Considering the typical indicators of ISs at national level, we may observe that, in line with global trends (WIPO, 2018), the number of patents obtained by Latin American actors grew during the period under study. However, the region still lags far behind North America, Europe and Asia (WIPO, 2018). In the same vein, since the end of the 20th century, scientific production of Latin American countries has increased, achieving just over 5% of worldwide scientific publications (Confraria and Vargas, 2019). However, the region continues playing a peripheral role in the global research system, registering structural delays with respect to more developed regions (Crespi and Dutrenit, 2014).

These outcome indicators are clearly associated to resources devoted to innovation in Latin America. Average national expenditure in R&D is well below that of most dynamic regions, remaining in most Latin American countries below 1% of GDP (UNESCO, 2015; OECD 2020). Moreover, in Latin America the public sector leads with around 60% of the investment in R&D activities. Meanwhile, in developed countries, most of these investments come from business organizations (OECD, 2020). In the same vein, the number of researchers in the economically active population is five times less in Latin American countries than in small OECD' countries (UNESCO 2015). In addition, most researchers and PhD degree holders work in academia while

very few work in the private sector. This aspect, together with the structure of R&D expenditure, has been considered a major developmental constraint in the region. These constraints hinder the evolution of interactive feedbacks of creation, exchange and use of knowledge, reproducing disarticulated subsystems (Yoguel and Robert, 2010; Teixeira et al., 2020; Sábato and Botana, 2021) and hindering the formation of absorptive capacities in the region (Castellacci and Natera, 2016).

The original concept of absorptive capacities highlights the “two faces” of knowledge creation processes inside firms. Knowledge-creation activities create technical solutions but, also, allow exchanging and absorbing knowledge (Cohen and Levinthal, 1989 and 1990). This means that in order to learn interactively, the firm must know about the characteristics and potential uses of the knowledge exchanged, and, in turn, to know, it is necessary for the firm to engage in knowledge creation activities. Hence, the firm’s capacities are built in an interactive and cumulative trajectory according to their previous knowledge base (Teixeira *et al.*, 2020)

Following these theoretical premises, the concept of absorptive capacities was adapted in empirical studies at the national systems level (Filipetti et al., 2017). According to this literature, not only firms but also countries could have the capacity to recognize, assimilate and apply valuable knowledge. However, it is not easy to translate these complex concepts to indicators that fully capture their main attributes.

Previous studies used input and output indicators of science, technology and innovation to approximate the concept of absorptive capacities at national level, stressing the importance of national absorptive capacities to access external knowledge fluxes (Criscuolo and Narula, 2008; Castellacci and Natera, 2016; Filipetti et al., 2017). In the same vein, empirical evidence has recently shown that adequate absorptive capacity is a necessary condition for open ISs to achieve positive knowledge spillovers from trade and investment flows (Álvarez *et al.*, 2019).

These empirical studies, which have focused on measuring innovation activities or outcomes using different econometric techniques, have advanced our understanding of the role absorptive and connectivity capacities play in the performance of Latin American ISs. However, these measures cannot capture the interactive nature of systemic innovation. Therefore, we propose a different analytical approach aimed at reflecting interactions among actors involved in innovation processes and, particularly, at analysing the systemic disconnections widely observed in the (under)development path of Latin American countries.

3. Absorptive and connectivity capacities in ISs

External connectivity to access knowledge flows and local absorptive capacity are two critical building blocks in the functioning of ISs. The interaction between these system components in developing countries may be associated to the peripheral conditions of their ISs, which affect their access to frontier knowledge. In addition, in Latin America, these two capacities are constrained by the structural heterogeneities (i.e. systemic disconnections) that hinder virtuous learning cycles between knowledge production and the productive infrastructure (Cimoli and Porcile, 2009; Srinivas 2018; Chaves et al., 2020).

We understand that the development of the absorptive capacities of an IS is determined by the cohesion of internal systemic linkages, as counterpart of the structural disconnections affecting learning processes in developing countries. The internal cohesion of linkages reflects the critical mass of the system, which supports the exchange and use of knowledge within the IS. Conversely, when an IS lacks a critical mass of interactions, the degree of cohesion reveals systemic disconnections and the extent to which an IS depends on one or some system components (Erbes *et al.*, 2010; Dutrénit and Puchet, 2011; Srinivas, 2018).

According to this view, the uneven evolution of ISs in developed and underdeveloped countries may be observed from the interaction between a system's absorptive and connectivity capacities, which determine systemic outcomes that are not directly attributable either to a unique system component or to the sum of their isolated effects. A cohesive and externally connected IS will develop a critical mass of interactions that, through a process of creative destruction, changes the structure of the system in a virtuous circle that connects formerly separated subsystems. On the contrary, underdeveloped ISs are characterized by weak interactions, whose cumulative effects hinder the formation of a critical mass, both in volume and diversity. These feedback processes, in turn, limit the development of absorptive and connectivity capacities, so the systems of production and exchange of knowledge remain locked-in, usually around relatively less complex problems, in disconnected sub-systems (Cimoli and Porcile, 2009; Yoguel and Robert, 2010; Srinivas, 2018; Hartmann et al., 2021).

3.1. A social network approach to innovation system capacities

The ISs and social network analysis approaches are strongly intertwined and have been mutually influenced (Dolfsma and Leydesdorff, 2011), in particular regarding the study of systemic and networks properties which emerge from interactions.

The IS approach, beyond its strengths, presents some limitations to empirically identify and measure interactive effects, mainly in underdeveloped context,

where ISs usually lack interactive dynamics (Chudnovsky, 1999; Arocena and Sutz, 2000a). Conversely, the social network analysis approach is particularly suitable to capture the effects of interactive behaviour, considering the interactions in the whole system as a unit of analysis. Previous studies have found evidence that certain network structural properties facilitate innovation processes by improving cooperation mechanisms and information diffusion. In line with previous definitions based on the IS approach (Fagerberg and Srholec, 2017), such network structures comprise interactions and represent some sorts of collective capacities that belong to (and depend on) the interaction between agents who are simultaneously embedded in a certain network (Galaso, 2018).

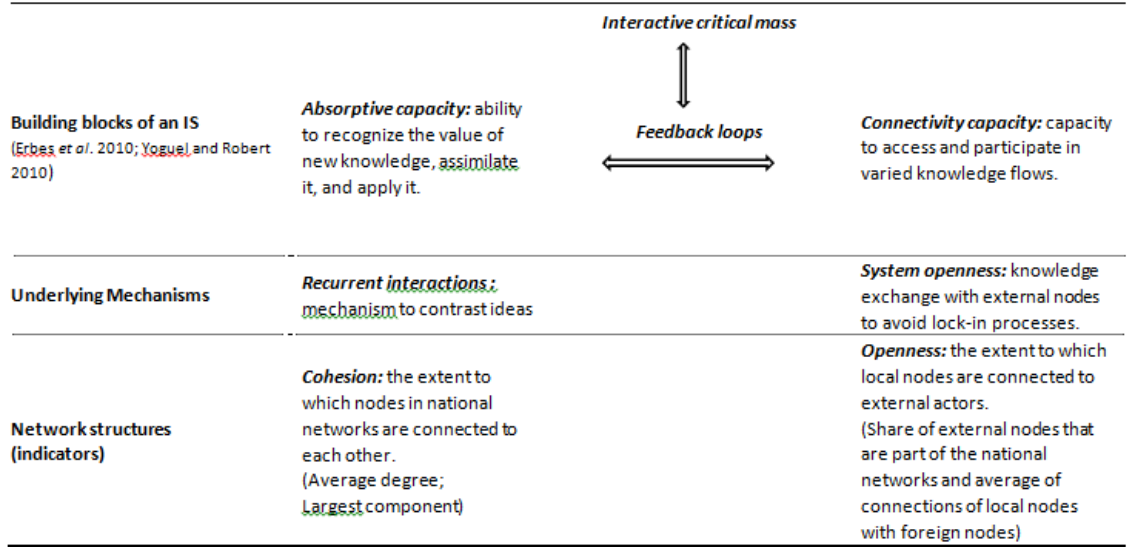
Following this stream of research, we conceive that absorptive capacity emerges from recurrent interactions between the IS's agents (Figure 1). Hence, from a network approach, the absorptive capacity can be approximated by considering *network cohesion*. The degree of cohesion denotes the extent to which nodes in the system are connected to each other, forming cohesive groups as opposed to being separate components isolated from each other. In other words, a cohesive network is one in which its nodes maintain many links with each other so that different connections can be established and knowledge can flow easily from one to another. Preceding literature shows that cohesive networks facilitate information access, making information more reliable and facilitating knowledge spillovers (Fritsch and Kauffeld-Monz, 2010), while fragmented networks restrict the flow of ideas, which can hamper innovation (Fleming et al., 2007).

External connectivity capacity can be assessed by analysing the *network openness*, which denotes the extent to which local nodes are connected to actors located in other territories. In national collaboration networks, system openness indicates the degree to which a country is connected with foreign inventors or owners (Andersson et al., 2019). Studies within the social network analysis literature have also found evidence that connections with external nodes can infuse new ideas into the local community, serving as non-redundant information channels (Lobo and Strumsky, 2008) and providing access to novel information that, otherwise, would not be available to local actors (Breschi and Lenzi, 2016; Crespo et al., 2016).

In peripheral regions, openness is essential for IS to access and absorb new knowledge. However, studies at both country and firm level (Marín and Bell, 2006; Filipetti et al., 2017) have found heterogeneous effects of openness strategies, showing that the positive effects of external openness to knowledge flows are only achieved by agents that absorb inbound knowledge while generating local knowledge flows. By contrast, if the fluxes are only inbound, the openness process can derivate in knowledge dependence on external agents.

Figure 1 summarizes our analytical framework, showing how we translate the theoretical definitions of the two building blocks of the IS approach (absorptive capacity and connectivity capacity) into indicators for analysing the structural properties of the networks.

Figure 1. From theoretical definition to measurable network properties



Source: Authors

4. Data and methods

We use US patent records retrieved from the PatentsView platform (<https://www.patentsview.org>) which collects and organizes data from the USPTO. We select a database that includes 17,942 Latin American patents registered between 1970 and 2017, considering the application date to define the period under analysis. We study patents with at least one inventor, individuals who claim to have invented the patented technology, residing in a Latin American country (Table 1). In addition, we consider the owners of the patents (assignees), who can be organizations (i.e. firms, universities or research centres) or individuals.¹

We elaborate both networks of inventors and networks of patent owners. A link connecting two inventors is traced when they are registered in the same patent. Thus, co-invention links represent collaboration between at least two inventors who have patented the same product or process. In co-owner networks, the nodes are the patent assignees, and two or more owners are connected if they have worked with the same inventor. Thus, inventors are used as links connecting owners in this type of network (Graf and Henning, 2010). We also include in the national networks those foreign actors who collaborate directly with local inventors or owners.

Table 1. USPTO patents registered by Latin American inventors 1970-2017

Country	Patents	Inventors	Owners
Argentina	2338	1942	248
Bolivia	52	31	3
Brazil	6715	7760	969
Chile	950	1066	208
Colombia	589	662	95
Costa Rica	414	223	21
Cuba	179	819	54
Dominican Rep.	80	56	4
Ecuador	129	82	8
El Salvador	28	26	4
Guatemala	65	46	6
Honduras	39	24	1
Mexico	5184	5598	477
Nicaragua	11	9	NA
Panama	137	70	30
Peru	210	166	24
Paraguay	19	18	2
El Salvador	28	26	4
Uruguay	171	146	31
Venezuela	1094	908	57

Source: Authors, based on PatentsView data.

Regarding the temporal evolution of the networks, we consider eight-year windows. For each temporal window, we trace the type of networks described above, considering only nodes and links that occur within that time period.

To capture the absorptive capacity of IS, we calculate two indicators (Table 2). First, the average degree, which measures in a simple and clear way the average level of interaction between network actors. This indicator is particularly suitable for comparing cohesion in networks of different sizes (unlike others also used in the literature, such as the density index, which are very sensitive to network size). Our second indicator of cohesion is the size of the largest component of the network. Some types of networks (such as patent networks) are fragmented into different groups of nodes, forming a sort of constellation of components. When the largest component agglutinates a high proportion of the nodes, then the network is less fragmented. The literature on the evolution of networks has found that as the number of links in a network increases, the network becomes progressively more cohesive, forming larger and larger components. This process of gradual cohesion changes when a tipping point is reached abruptly, and the emergence of a “giant component” brings a significant proportion of the nodes together (Jackson, 2008; Fleming, et al., 2007).

To measure network openness (external connectivity capacity), we use two simple network indicators: foreign nodes and foreign links. In the Latin American patent networks, there are some actors (inventors or owners) located in foreign countries that maintain collaborative links with the local actors of the network. Taking this into account, the first indicator of connectivity capacity, the number of foreign links, is measured in terms of the number of connections that local actors maintain with foreign actors. The second indicator focuses on the number of foreign actors that participate in local patents by collaborating with local actors. The combination of these two indicators allows us to measure the extent to which a national network is open and connected to external actors.

Table 2. Network measures for the key concepts

Concept	Measure	Description
Absorptive capacities	Average degree	The average degree is the average number of links connecting to each node in the network
	Size of largest component	The largest set of nodes whose members are directly or indirectly connected to each other and disconnected from the rest of the network
Connectivity Capacities	Foreign actors	The share of external nodes that are part of the national networks
	Foreign links	The share of links between local and foreign nodes over the total number of links in the network

Source: Authors

This methodology has a number of limitations. It offers only a partial picture of ISs as we analyse collaborative ties in knowledge-creation activities and knowledge-appropriation processes related to patentable knowledge. However, this empirical approach captures neither informal knowledge exchanges nor knowledge appropriated through other protection mechanisms.

On the other hand, an extensive literature has documented that patents are a problematic indicator of innovation outputs because most innovations are not patented and only around half of the patents owned by firms are used or licensed. Moreover, the use of a patent system to protect invention rights is highly heterogeneous (Nagaoka et al., 2010). In particular, in developing countries the firms' incentives to patent are lesser than in the developed ones (Dolfsma and Leydesdorff, 2011).

However, using patent information to trace collaborative inventive activities produces a consistent –albeit partial– measure of systemic knowledge exchanges (Dolfsma and Leydesdorff, 2011). Furthermore, the use of a common patent regime allows an adequate comparison of inventive activities between countries, avoiding problems associated with the institutional differences

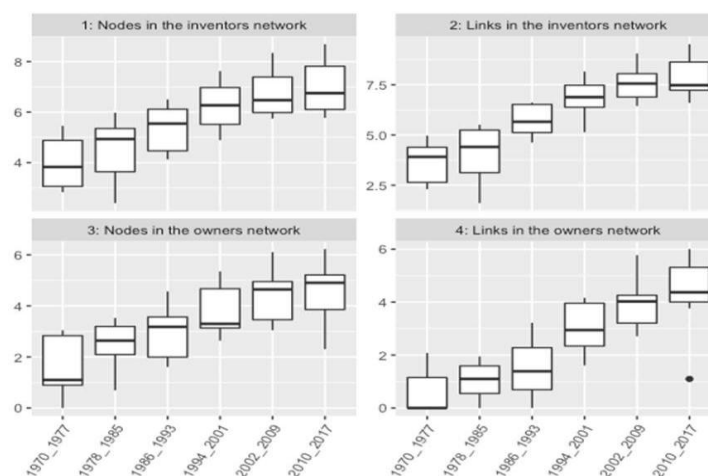
among national patent offices. In this regard, the US patent system has the advantage of being the world center of the market for technology, at least during the period studied.

It should be noted that the empirical evidence presented here is mainly descriptive. A great deal of previous research has analysed in depth different national and sectoral cases. Therefore, we analyse the evolution of the collaborative patenting networks in Latin American countries, as indicators of critical attributes of the Latin American ISs, against the backdrop of this prior research.

5. Addressing Latin American ISs through collaborative networks

Patent collaboration networks of Latin American countries are very heterogeneous in terms of size. As presented in Figure 2, these networks grew during the period under study, since their number of both nodes and links increased. This is observed for both inventor and owner networks, and for all countries in the region; however, as we will see below, this growth is not constant in all networks and some countries even experienced some years of network retraction.

Figure 2. Evolution of the size of country networks



Notes: The size of the boxes represent the interquartile range (IQR), the horizontal line inside each box represents the mean, the vertical lines represent the minimum and maximum excluding outliers, the dots represent outliers. The outliers are observations that lie over the $Q3+1.5*IQR$, or below $Q1-1.5*IQR$.

Table 3 shows the overall results of the absorptive and connectivity capacities of Latin American ISs. First, with respect to absorptive capacities, we can observe that, although the average degree increases during these years, network cohesion remains very low. This can be also observed with the largest component indicator, which, in most countries, accounts for only a small proportion of the nodes (Table 3), indicating that patent networks in Latin

American countries are highly fragmented, i.e. made up of a constellation of small components isolated from each other.

Fragmentation is particularly high in inventor networks –except in the case of Cuba, which is a clear outlier in this aspect– since in all countries the largest component never reaches 20% of nodes and for most countries it does not even reach 10%. As reference values, Bettencourt et al. (2007), Breschi and Lenzi (2015) and Casper (2013) document values above 50% in inventor networks in several US regions. More recently, Pinto et al. (2021) report a largest component with almost 80% of the nodes (except for isolated inventors) for the network of all USTPO inventors.

On the other hand, the owner networks are slightly more cohesive, since the proportion of nodes connected to the largest component is higher, which is in line with previous studies in other countries. For example, Galaso and Kovarik (2021) and Graf and Henning (2010) documented the largest components of similar sizes in Spanish and German regions respectively. However, these owner networks present very small and simple structures. That is, with few exceptions, they are essentially made up of groups of owners that collaborate on a single patent but are not linked to any others, and, therefore, these groups remain isolated from each other.

Table 3. Summary of network statistics in Latin American countries

	Inventors networks		Owners networks	
	1970-77	2010-17	1970-77	2010-17
Absorptive capacities				
<i>Av. Degree</i>				
Mean	1.705	5.146	0.208	1.922
Median	1.222	4.551	0	1.600
Max.	5.444	9.763	0.824	4.452
	(CU)	(CU)	(AR)	(CU)
Min.	0.7556	3.907	0	0.444
	(VE)	(CO)	(CL/CO/CU/VE)	(VE)
<i>Share of largest component</i>				
Mean	0.147	0.114	0.354	0.277
Median	0.089	0.042	0.200	0.143
Max.	0.5	0.533	1	0.806
	(CU)	(CU)	(CL)	(CU)
Min.	0.038	0.035	0	0.053
	(BR)	(CL)	(CU)	(MX)
Connectivity capacities				
<i>External links</i>				
Mean	0.176	0.467	0.020	0.328
Median	0.168	0.491	0	0.257
Max.	0.444	0.683	0.1429	0.684
	(CL)	(CU)	(BR)	(CU)
Min.	0	0.248	0	0.156
	(CU)	(CL)	(MX/AR/CL/CO/CU/VE)	(MX)
<i>External nodes</i>				
Mean	0.208	0.381	0.010	0.215
Median	0.209	0.379	0	0.167
Max.	0.438	0.495	0.067	0.387
	(CL)	(VE)	(BR)	(CU)
Min.	0	0.193	0	0.111
	(CU)	(CU)	(MX/AR/CL/CO/CU/VE)	(VE)

Source: Authors, based on PatentsView data.

The fragmentation of national networks into isolated teams of actors represents an important barrier to the circulation of ideas and the absorption of new knowledge. This suggests that collaborative networks replicate the IS structure composed of disconnected subsystems (Cimoli and Porcile, 2009; Srinivas, 2018).

Regarding connectivity capacities, Latin American ISs have traditionally been open systems. Co-invention networks between 1970 and 2017 consistently include a large number of inventors from outside the region. However, since 2000, the share of external inventors has stopped growing, and, indeed, it seems to have declined in several countries. Despite this, the proportion of external inventors at the end of the period is high, with values above 40% in most countries and above 50% in some of them. These proportions are significantly higher than those reported in inventor networks in the USA (Fleming et al., 2007; Lobo and Strumsky, 2008). On the other hand, owner networks show a greater involvement of external actors and an increase in the percentage of foreign owners after 1990, which accords with the economic openness process of the late twentieth century. In parallel with this increasing openness, the growth of patent activity in the region has been supported by growth in the absolute number of local actors, both owners and inventors.

These results reflect the effects of structural reforms Latin American countries pursued after the 1990s. In this context, our results suggest that the market expansion and increased competition associated with economic liberalization have not increased invention and innovation in the region, but they have shown the limits of knowledge reception capacity in the absence of strong local absorptive capacities (Montobbio and Sterzi, 2011; Campi and Dueñas, 2019).

We now focus on analysing the absorptive and connectivity capacities in those countries with the largest networks in Latin America. Table 4 presents the indicators of these capacities for these countries at the end of the period (2010-2017) and a summary of the distinctive features of their networks. Figure 3 shows, for each country, the combinations of absorptive and connectivity capacities at different points in time, reflecting the relationship between the two capacities.

Table 4. Absorptive and connectivity capacity indicators, 2010-2017. Summary

Country	Network's key features	Absorptive Capacities				Connectivity capacities			
		Inventors		Owners		Inventors		Owners	
		Share largest component	Average Degree	Share largest component	Average Degree	Foreign links	Foreign nodes	Foreign links	Foreign nodes
Brazil	The largest networks in the region. Rapid growth.	0.05	4.596	0.143	1.6	0.491	0.365	0.329	0.174
Mexico	Large networks and rapid growth, especially in the inventors' network.	0.042	4.285	0.053	1.699	0.514	0.379	0.156	0.167
Argentina	Well cohesive network of owners, where a giant component has emerged.	0.037	4.778	0.348	2.874	0.494	0.459	0.432	0.348
Chile	Large and well-cohesive network of owners.	0.035	4.141	0.127	1.164	0.248	0.372	0.257	0.157
Cuba	Both networks are very cohesive. Inventors' network is the only one on the continent with a giant component. Well connected to foreign nodes.	0.533	9.763	0.806	4.452	0.683	0.193	0.684	0.387
Colombia	Small (relative to the country size) and poorly connected networks.	0.042	3.907	0.13	1.217	0.352	0.402	0.19	0.159
Venezuela	Emergence and subsequent disintegration of a giant component in the inventors network.	0.059	4.551	0.333	0.444	0.485	0.495	0.25	0.111

Source: authors based on PatentsView data

Figure 3. Network cohesion and openness in Latin American ISs

Figure 3a. Plot of average degree vs. percentage of foreign links in invention networks

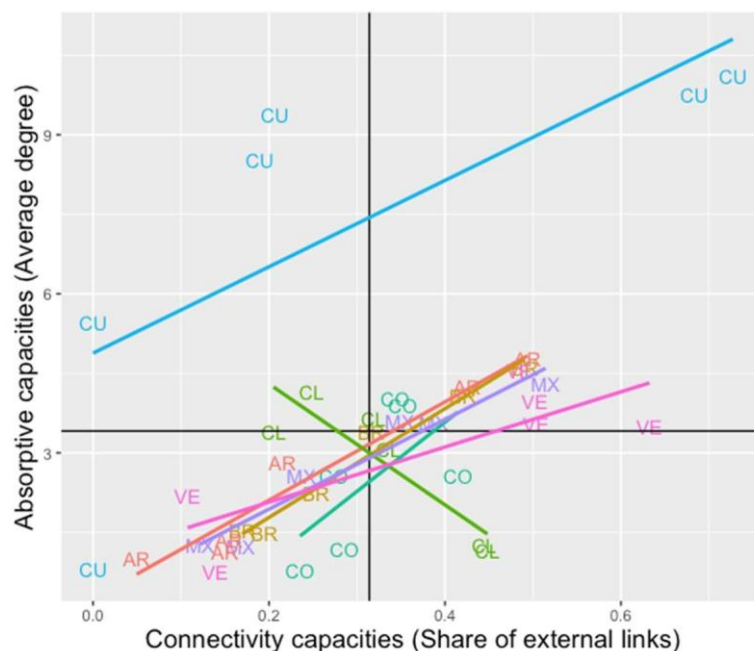
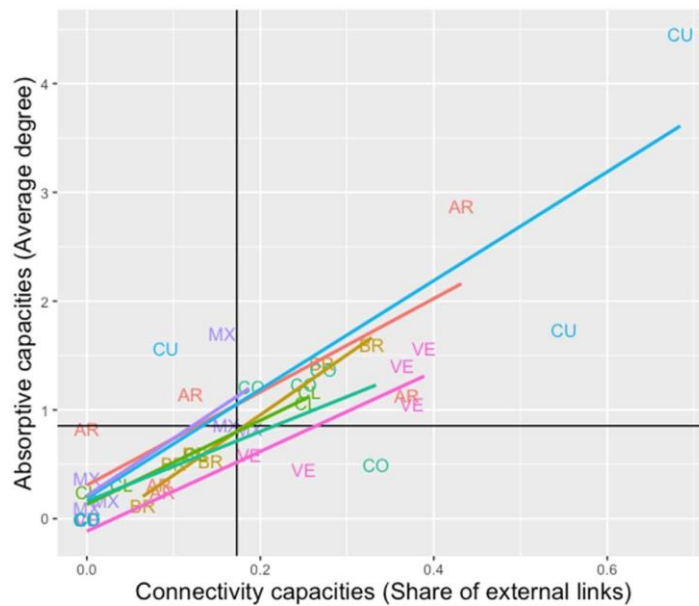


Figure 3b. Plot of average degree vs. foreign links in owner networks



Source: Authors, based on PatentsView data.

Notes: cohesion indicators on y-axes, openness indicators on x-axes. AR=Argentina; BR= Brazil; CL=Chile; CO= Colombia; CU= Cuba; MX=Mexico; VE= Venezuela.

This analysis yields two main findings. First, we see some diversity in inventor and owner networks, with some countries, such as Cuba, standing out particularly for their inventor network.

Second, we appreciate a positive correlation between connectivity and absorptive capacities (Figure 3), which is robust when different indicators are used. The intensity of this relationship seems to vary from country to country, and we also find some interesting exceptions, such as Chile, which exhibits a negative correlation between absorptive and connectivity capacities in the inventor network.

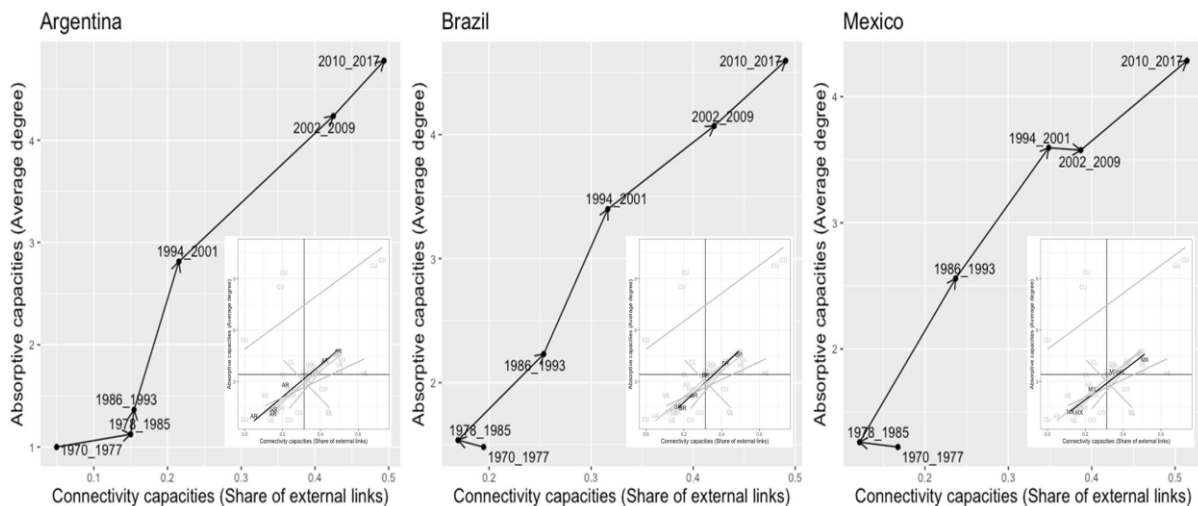
5.1. The big three: Brazil, Mexico and Argentina.

The largest countries of the region differ greatly in terms of geographical location, productive structure, trade specialization, and research infrastructure. However, these countries share a regional leader position. Since the period of state-led industrialization, these countries have built national innovation capacities, sometimes anchored in large national development projects (Cimoli and Katz, 2003; De Negri, 2010). Jointly with the formation of the scientific systems in the 1950 and 1960 decades, these processes support the formation of a critical mass of scientific actors in some specific fields (Dutrénit and Puchet, 2011).

In addition, during the 48 years analysed here, these three ISs all exhibit a positive correlation between absorptive and connectivity capacities in inventor networks as well as a consistent increase in both capacities (Figure 4). On the other hand, the owner networks in these countries also show a mostly positive but nonmonotonic correlation between absorptive and connectivity capacities (Appendix A4).

Several studies have analysed these cases in depth (e.g. De Negri, 2011), showing that their ISs are made up of heterogeneous agents, with a low density of internal linkages and the existence of some highly developed fields, usually geographically concentrated in the most affluent regions of the country (de Araújo et al., 2019). According to our results, these ISs exhibit relatively large and cohesive co-invention and co-appropriation networks. The network indicators also show that absorptive capacities have evolved similarly in Brazil and Mexico. These countries improved the average degree and substantially increased the size of the largest components in both inventor and owner networks. This is especially clear in the Brazilian inventor network where its largest component has grown to around 300 nodes by the end of the period (Appendix, Figure A1). Meanwhile, in co-appropriation networks, Argentina exhibits an impressive growth of the largest component, showing a considerable improvement of owner network cohesion (Appendix, Figure A4).

Figure 4. Coevolution of absorptive and connectivity capacities in Brazil, Mexico and Argentina



Source: Authors, based on PatentsView data.

However, in these networks, the largest components represent only a very small proportion of all the nodes. This indicates that none of the three countries has yet experienced the emergence of a giant component, so their networks, as a whole, are still very fragmented, with a prevalence of weak systemic interactions co-existing with a few relatively large and well-connected components (Rivera-Ríos et al., 2009). The owner network in Argentina is an

exception to the above, since the largest component brings together more than a third of its nodes. Thus, we could consider that a giant component has emerged in this network. This feature should substantially facilitate the circulation of knowledge among patent owners, which implies a strength in the absorptive capacity of the Argentine IS.

Regarding the connectivity capacities, these three largest ISs have relatively few foreign nodes (Appendix, Figures A1-A3). However, the proportion of foreign inventors in the Argentinean and Mexican networks has been steadily increasing, from approximately 25% in the 1970s to more than 40% in the 2000s. By contrast, the proportion of foreign inventors in Brazil's networks has systematically decreased, from 46% in the 1970s to 37% in the 2000s.

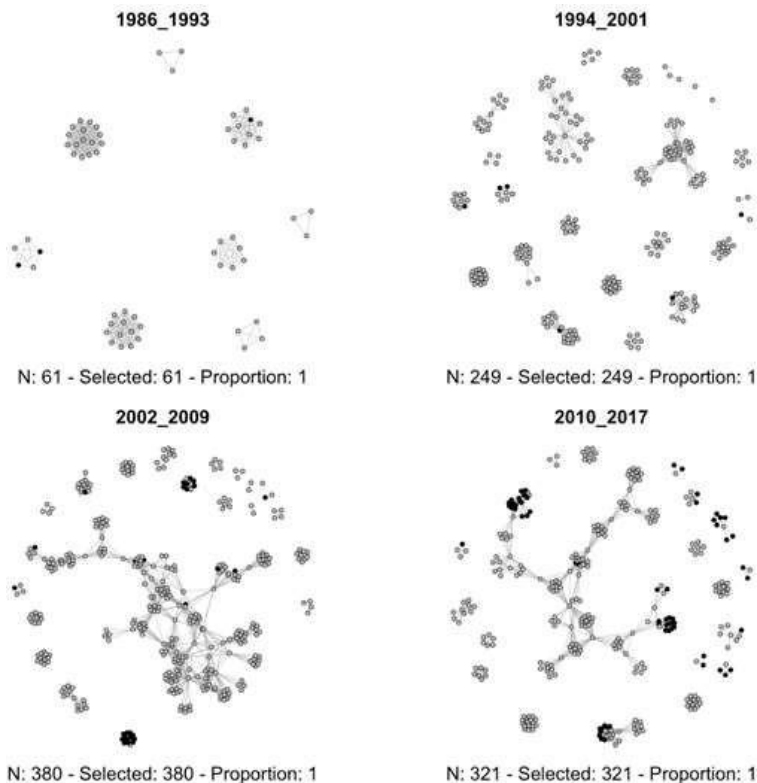
In sum, our results confirm that the Brazilian IS, which is strongly supported by national policies, is the most mature IS in the region. Brazil has progressively accessed to the global system of knowledge, exhibiting increasing collaboration with Asian partners in addition to long-standing collaborations with partners in Europe and the U.S. (Ponomariov and Toivanen, 2014; Reis et al., 2018). Meanwhile, Mexico seems stuck in an unbalanced relationship with the United States that hinders the formation of a local critical mass (Dutrénit and Puchet, 2011). As for Argentina, the most intriguing finding is its highly cohesive owner network, which is inconsistent with (and arguably contrary to) previous evidence of a lack of collaborative innovation linkages in the Argentinean IS (Erbes et al., 2010; Chudnovsky, 1999).

5.2. Chile and Cuba: a tale of two development projects

The evolution and current state of collaborative patent networks in Cuba and Chile seem to be related to explicit national projects, which have been recently discussed in each country (Atria et al., 2012; Rodríguez and Núñez, 2021). The former is noteworthy for the structure of its inventor network and the latter for the relative importance of its owner network.

The Cuban co-inventor network is, by far, the most cohesive network in the region: it has no isolated actors and its inventors have, on average, twice as many connections as the next-most-cohesive ISs in the region. In the rest of Latin American countries, the largest connected components of co-inventor networks include only a small proportion of the nodes. In the Cuban network, however, the largest component accounts for more than 50% of the nodes (Table 4). In fact, Cuba is the only Latin American country in which a giant component has emerged since 2002 (Table 4, Figure 5).

Figure 5. Evolution of Cuba inventor network



Note: Grey nodes represent Latin American inventors; black nodes represent foreign inventors. N: total number of nodes in each period; Selected: number of nodes represented in each graph; Proportion=Selected/N.

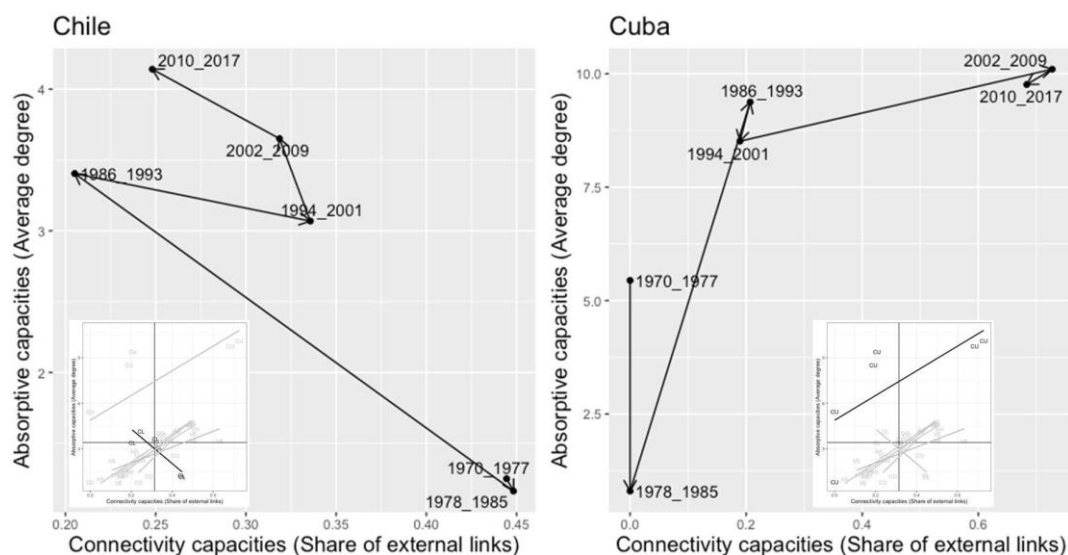
Despite the exceptional evolution of the Cuban co-inventor network, its national co-owner network is quite small but very cohesive. The difference between the co-inventor and the co-owner networks reflects the structural features of the Cuban IS, where a high degree of scientific development coexists with a relatively weak and extremely concentrated business ecosystem, life sciences being the country's strongest sector (Kwon et al., 2014). In fact, patenting activities in Cuba are mostly conducted by a number of state-owned enterprises that pursue a national strategy of innovation that survived a severe crisis following the dissolution of the socialist bloc (Blanco, 2020). Nowadays, exports of pharmaceutical and biotech products are part of the island's international trade strategy, which contributes critically-needed revenue to the national economy (Kwon et al., 2019).

Conversely, Chile stands out because its owner networks are better connected than its co-inventor networks. We observe in the Chilean case that absorptive capacities in co-inventor network have not improved since 1986, while the co-owner network has greatly increased its size and cohesion. Previous studies have shown evidence of the improvement and increased dynamism of Chile's system of entrepreneurship during the last decade (Klerkx et al., 2015) and the relative success of using public funds to support firms' interactive innovation

projects (Crespi et al., 2020). However, a number of empirical studies have emphasized the weak cohesion of the Chilean IS (Pinto et al., 2019) and the low level of private investment, even in highly competitive industries (Bas and Kunc, 2009). As mentioned above regarding the Argentinean owner network, our results do not fully accord with the extant evidence on the cohesion and interactive dynamics of the business sectors in these countries. Explaining this discrepancy is a task for future research.

Cuba exhibits interesting results regarding external connectivity capacity. On the one hand, according to the share of foreign nodes in its network, Cuba exhibits the least externally oriented network in the region. Meanwhile, the Cuban network ranks highest in the region for number of links with external actors. Because of the national development project (Rodríguez and Núñez, 2021), the Cuban IS exhibits a uniquely high level of absorptive capacity together with focussed external connectivity capacities. Certain nodes, in particular state-owned firms, seem to play the role of gatekeepers (Graf, 2011), i.e. they intermediate between local nodes and external actors (Rodríguez and Núñez, 2021). Gatekeepers may contribute to overcoming subsystems' previous disconnection, as interpreted by Cuban authors (Blanco, 2020; Rodríguez and Núñez, 2021). However, intermediary state-owned firms may also operate by controlling the diffusion of external knowledge along the Cuban IS.

Figure 6. Coevolution of absorptive and connectivity capacities in Chile and Cuba



Relatedly, these two countries show a unique relationship between absorptive and connectivity capacities. Chile is the only case in the region that exhibits a negative correlation between the two dimensions (Figure 6, left), which is reflected in its changing trajectory: it started out relatively open and has been able to build greater absorptive capacity among inventors. Cuba, by contrast, exhibits the opposite trajectory; it started out relatively closed to foreign

collaboration and remained so until the 1980s, after which it has exhibited increasing openness together with increasing cohesiveness of the inventor network (Figure 6, right).

5.3. Uneven trajectories: The Venezuelan and the Colombian innovation systems

Patent network analysis reveals differences in the evolution of the Colombian and the Venezuelan ISs. These two countries have experienced internal and external pressures that have affected their economic and social stability. However, while Venezuela was traditionally seen as a relatively advanced IS in the region, its recent experiences—in particular, its recent national policies and political conflict—have adversely affected research and innovation activities in the country (Jimenez and García, 2017). By contrast, Colombia's policy on research and innovation is framed by a novel approach linking innovation and research with development goals (Colciencias, 2018). However, our results accord with the most recent research on the Colombian IS, showing a highly fragmented network (Correa et al., 2014; Gómez, 2018) and an erratic accumulation of both absorptive and connectivity capacities. In fact, although Colombia is the third-most-populous country in the region and its investment in research and innovation has recently grown, its networks are relatively small and its connectivity levels are also low. Our results suggest that the Colombian IS has failed to generate and maintain a critical mass of local inventors and patent owners. Arguably, as recent studies of this country show, these results may be related to the fact that the national patent network is highly concentrated around the national petroleum company (Gómez, 2018).

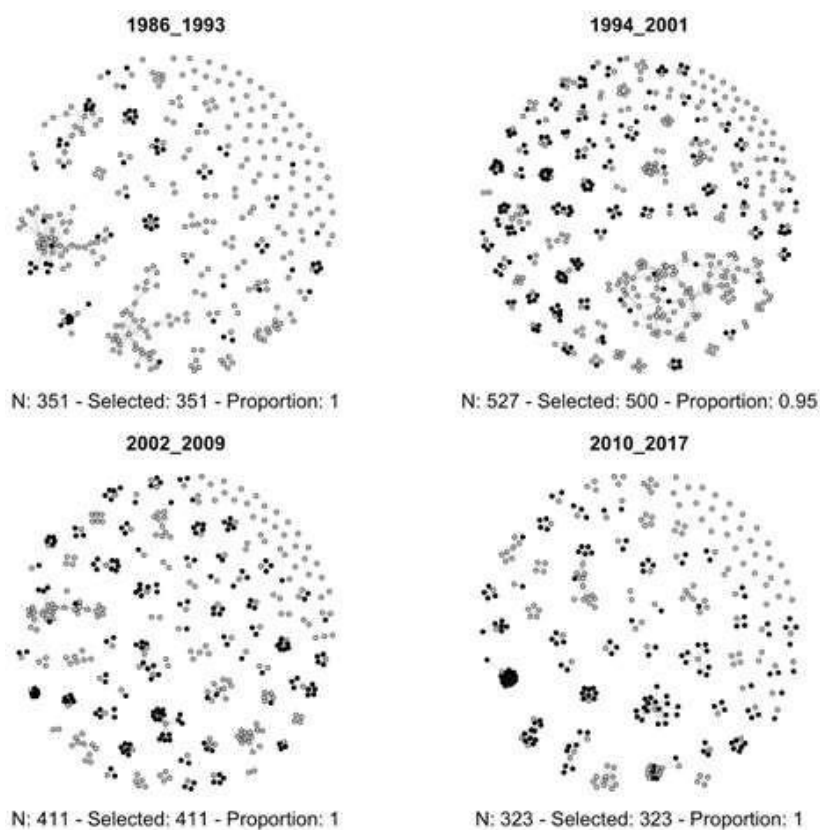
Around the petroleum research and production, the cases of Colombia and Venezuela provide new evidence on the relatively high level of development associated with a strategic resource for the country and the public policy created to support its development. However, these cases also reinforce the perception of disconnected subsystems, with heterogeneous levels of maturity and development, cohabiting within the same national IS.

The case of Venezuela is particularly interesting because of the evolution of its network cohesion. Both co-invention and co-appropriation networks evolved until about halfway through the period considered in this research and then they suffered a strong reduction in size and loss of cohesion in recent years, which seems to reflect a de-accumulation or de-learning process. While this sort of decay is viewed as a chronic curse of innovation processes in Latin America (Arocena and Sutz, 2000b; Sagasti, 2005), our analysis does not find it in any other network in the region. In Venezuela's co-invention network, we find that a giant component (more than 100 inventors representing 20% of the nodes) emerged in 1994 and, subsequently, disintegrated until in the most recent eight-year period it included only 19 nodes (Figure 7).

The rise and fall of a giant component in the Venezuelan co-invention network is contrary to what is expected from the network evolution literature where, after the emergence of a giant component, networks tend to remain cohesive (Jackson, 2008). Meanwhile, it is evident that the Venezuelan network has disintegrated. This finding seems to reflect the effects of the 2002 political crisis, associated to major strikes in the state-owned petroleum firm, and the massive emigration of scientists (Requena and Caputo, 2016). In fact, during the 1976-2010 period 80% of the Venezuelan patents registered in the USPTO (Requena, 2011) and 40% of the patents registered in the national intellectual property office (Hall, 2005) were attributable to the national petroleum research institute.

Moreover, this country has exhibited a strong tendency towards international collaborations since 1986, which may indicate a weakening of its national collaboration networks and, therefore, a greater dependence on foreign actors.

Figure 7. Evolution of Venezuela inventor network

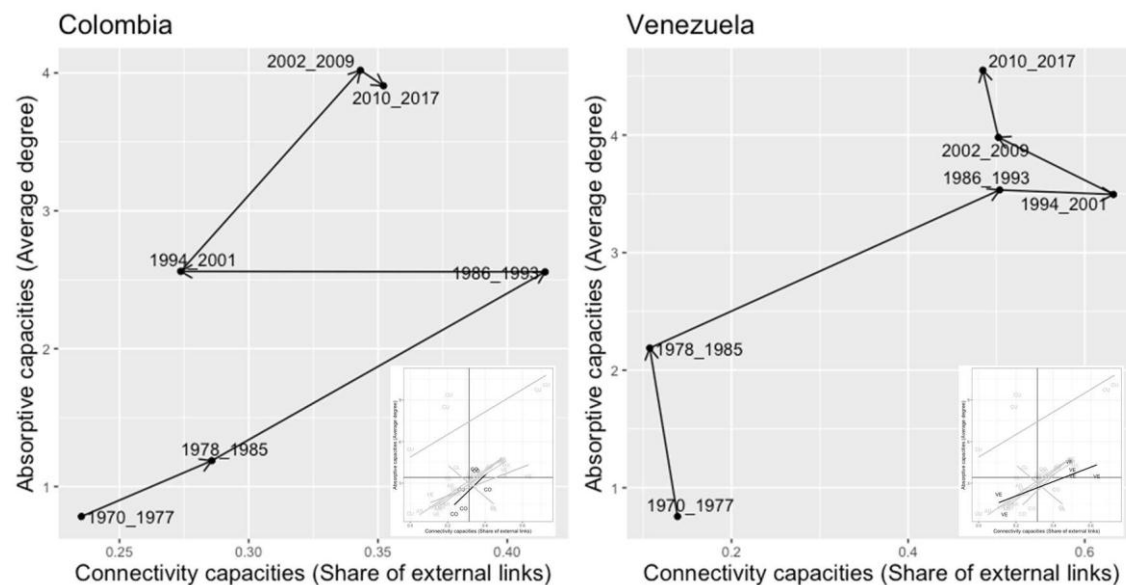


Note: Grey nodes represent Latin American inventors; black nodes represent foreign inventors. N: total number of nodes in each period; Selected: number of nodes represented in each graph; Proportion=Selected/N.

In spite of the differences between these two countries, the Colombian and Venezuelan networks share a highly uneven relationship between absorptive and connectivity capacities. Due, likely, to the political and civil crises in these

countries (Jiménez and García, 2017), both inventor and owner networks exhibit a significant decrease in accumulated absorptive capacity and, after 2010, an even greater decrease in connectivity capacity in owner networks (Figure 8).

Figure 8. Coevolution of absorptive and connectivity capacities in Colombia and Venezuela



Source: Authors, based on PatentsView data.

6. Final remarks and conclusions

This paper presents novel empirical evidence concerning patents and collaboration networks in Latin American countries between 1970 and 2017. Based on a dataset of patents registered with USPTO and using social network analysis techniques, we confirm certain structural features and identify recent critical changes in Latin American ISs. In addition, we apply a theoretical framework which maps system-theoretic properties onto critical IS attributes that are observable through network analysis. In particular, we contribute to measuring and analysing the elusive concept of national absorptive capacities (Criscuolo and Narula, 2008) using indicators that take interaction as the analytical unit. This allows us to analyse the critical mass of interactions as an emergent property that enables self-sustained system functioning.

Four major findings of this research merit emphasizing. First, collaboration networks in Latin America are not cohesive. We find a constellation of separate groups in national networks where the largest components encompass only a small share of network actors. According to network evolution models, networks tend to grow increasingly connected, as more links

appear, until they form complex, cohesive structures (Jackson, 2008). However, the networks in our analysis do not still show either complex structures or the critical mass of interaction needed for self-sustained system functioning (Dutrénit and Puchet, 2011). Second, despite this general lack of connectivity, certain national exceptions can be found. As we noted above, Cuba has a strongly cohesive co-invention network, while Argentina and Chile exhibit highly cohesive networks of owners. The differences we found between co-invention and co-appropriation networks illustrate distinctive features of national ISs, in particular the relatively low participation of private actors. Third, networks show a large number of international collaborations, indicating that many of the interactions associated with invention processes in Latin America are outward-oriented. Finally, the arguably most important finding is that, with the exception of Venezuela, all the largest Latin American ISs, despite exhibiting relatively low absorptive capacities, show a cumulative trend of increased systemic capacity. However, persistent signals of structural disconnections, attributable to disconnected subsystems, are registered.

Future research should seek to provide more in-depth national networks analyses that incorporate the characteristics of the agents involved in the interaction as well as the technological fields in which they operate.

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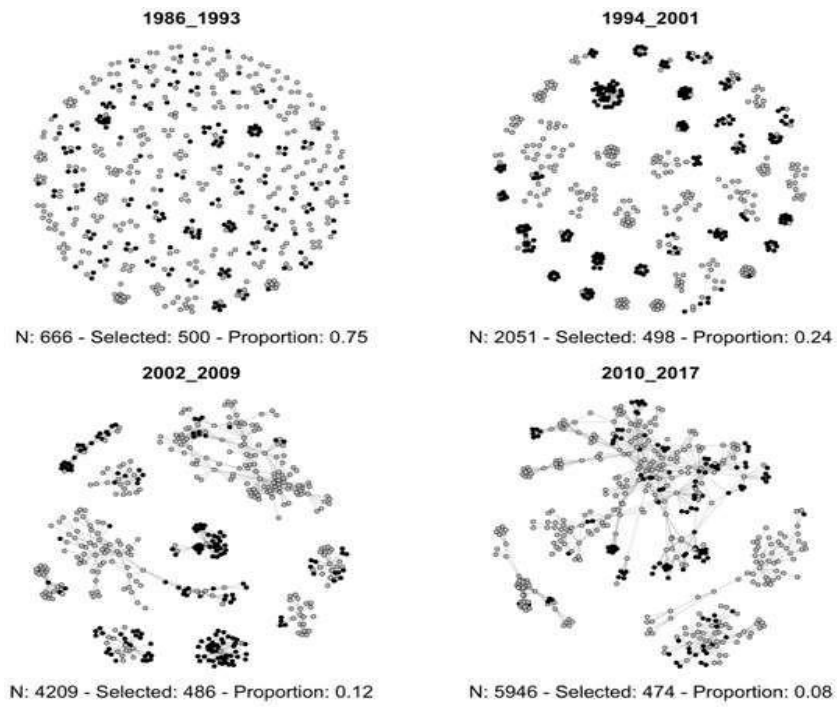
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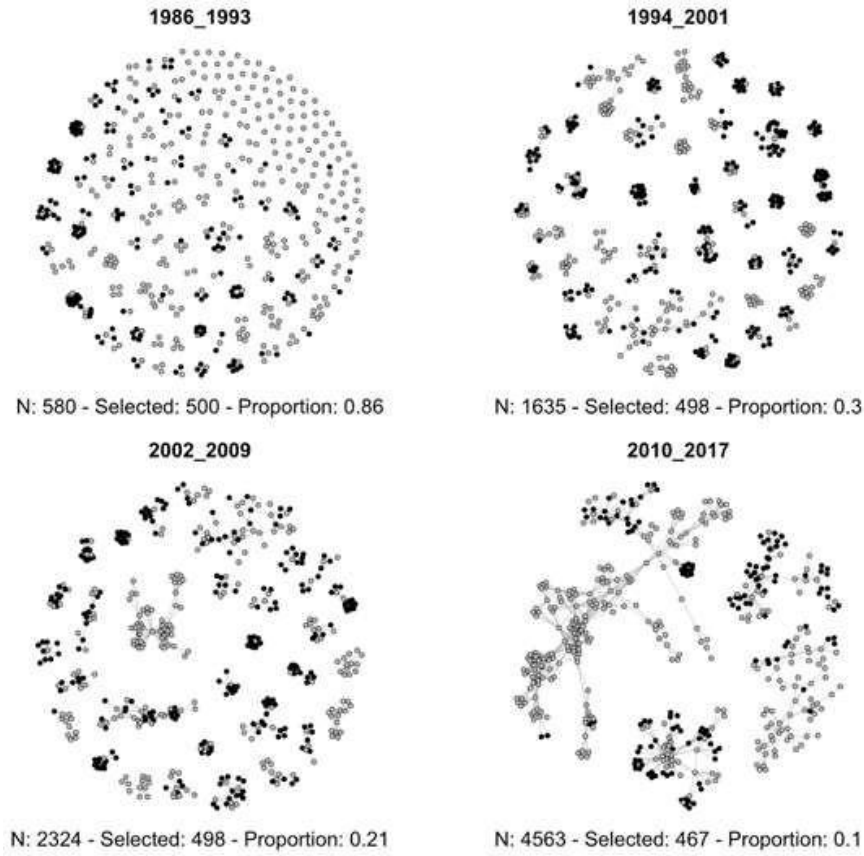
Appendix.

Figure A1. Evolution of Brazil inventor network



Note: Grey nodes represent Latin American inventors; black nodes represent foreign inventors. N: total number of nodes in each period; Selected: number of nodes represented in each graph; Proportion=Selected/N. Source: Authors, based on PatentsView data.

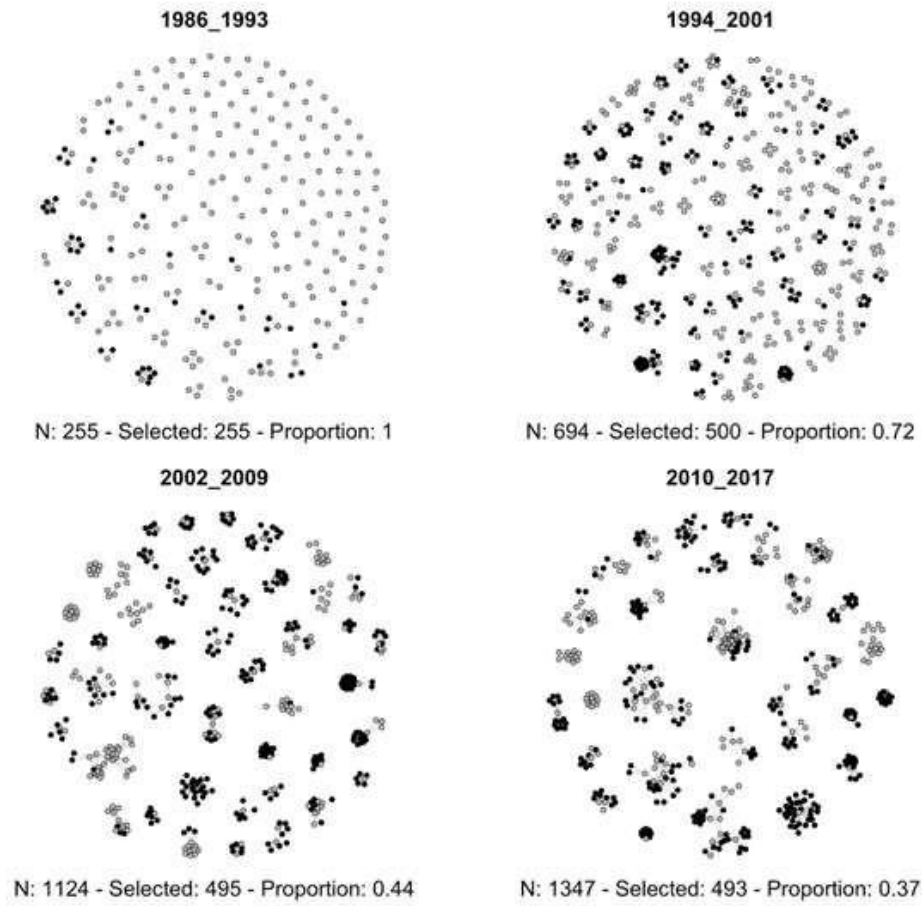
Figure A2. Evolution of Mexico inventor network



Note: Grey nodes represent Latin American inventors; black nodes represent foreign inventors N: total number of nodes in each period; Selected: number of nodes represented in each graph; Proportion=Selected/N.

Source: Authors, based on PatentsView data.

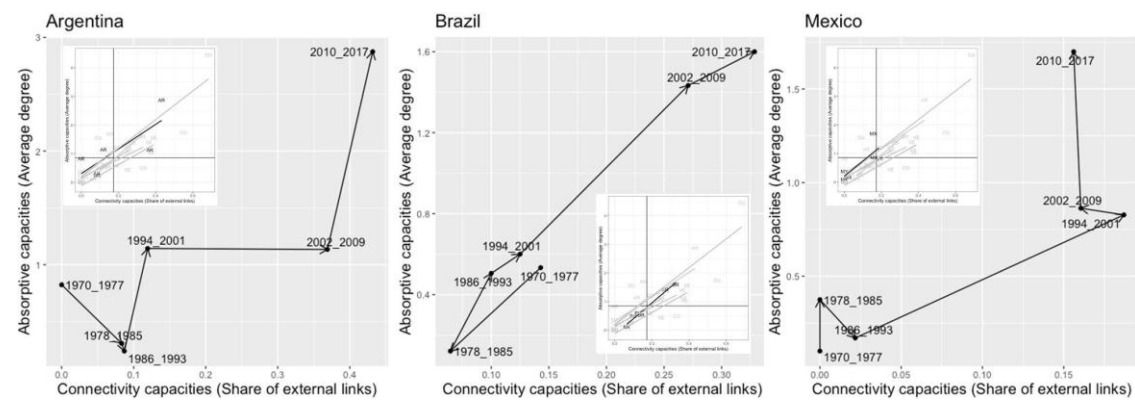
Figure A3. Evolution of Argentina inventor network



Note: Grey nodes represent Latin American inventors; black nodes represent foreign inventors. N: total number of nodes in each period; Selected: number of nodes represented in each graph; Proportion=Selected/N.

Source: Authors, based on PatentsView data.

Figure A4. Coevolution of absorptive and connectivity capacities in owner networks



Source: Authors, based on PatentsView data.

Notes

- ¹ A detailed explanation of the data selection and processing up to the reconstruction of our networks can be found in Authors.

Does Value of Information depend on Providers? Evidence from Indian Agricultural Households

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Abstract

Access to information by Indian farming households has stagnated at 41 percent for a whole decade even after implementation of decentralised policy towards information dissemination. This paper tries to estimate the impact of information use on technical efficiency of agricultural production in India using propensity score matching method. The study utilises cross-sectional data from the 70th Round of NSSO on Situation Assessment Survey of Farmers. Technical efficiency is calculated using a novel technique by Cherchye, et.al. (2013) that acknowledges the presence of multiple outputs, output-specific inputs and joint inputs in the data. The results of propensity score matching method show that users of information have a slightly higher efficiency than non-users but the impacts vary largely across different sources of information. The findings hint at a source effect working at large that tends to dampen the true effect of information further suggesting that value of information largely depends on the provider. Using information from private sources has the largest impact while media has a smaller impact. Public sources don't show a statistically significant impact, may be due to constraints like lack of infrastructure, manpower and monitoring. Nevertheless, it does not undermine their importance but suggests that they might work through indirect channels that require further exploration.

Keywords: Agriculture, Information Use, Technical Efficiency, Data Envelopment Analysis, Propensity Score Matching

1. Introduction

Agricultural growth is important for poverty reduction and economic growth in developing countries where a large part of the population is dependent on agriculture (Chakravarty, 1987, Timmer, 1988 and Johnson, 2000). The multiplier effect of agricultural growth on the non- farm sector has long been recognised (Byerlee et.al. 2009); especially since the seminal work of Schultz (1964). Thus, development of this sector becomes a core concern for scholars and policy makers in developing countries like India, where almost 60 percent of the population is dependent on it. One of the stylised facts of structural transformation is that during economic development the share of agriculture in output declines as does its share of employment but with a lag. In India, agriculture, with a 15 percent share in GDP remains the mainstay for nearly 60 percent (CSO, 2015) of our population. Indian agriculture is characterised by low productivity and pulling the sector out of this low productivity trap has been of utmost priority to ensure increase in farmers' income and growth of the sector and eventually the growth of the non-farm sector.

Several scholars have tried to address this problem through the lens of efficiency, technological innovation and policy intervention (Kalirajan and Shand, 1985; Kalirajan 1991; Fan 1991, 2000; Coelli and Battesse, 1996; Ghosh 1998; Bhalla, 2006; Fried et.al., 2008; Bardhan et.al. 2012). In all their studies, information has been attributed as one of the key catalysts in increasing productivity by reducing the gap between actual and potential output. When new technology becomes available, farmers do not automatically acquire the requisite skills to use it [Schultz (1964, 1975)]. Government interventions particularly in extension services, general education and rural infrastructure are expected to facilitate this process to speed up the adoption of new technology. In India, the government aims to bring farmers closer to information through various channels like Krishi Vigyan Kendras (farm science centres), Extension Agents, Agricultural Universities, veterinary departments and ICTs (newspaper, radio, television and internet). These sources are responsible for supplying the farmers with technical advice on different aspects of cultivation. Agricultural Technology Management Agency (ATMA), introduced in 2005, is one such novel initiative that aims at pluralistic demand-driven (bottom-up) approach to disseminate need-based information to farmers using public, private and non-profit channels. Despite these efforts, use of information remains quite low in India.

The National Sample Survey Organisation does a very comprehensive decadal survey on various aspects of Indian farming. The reports capturing the pre and post ATMA policy implementation show that access to information did not change for a decade, stagnating at 41 percent from 2002-03 to 2012-13 (NSSO, 59th Round, 2005; 70th Round, 2015); users of information were even lower,

only 35 percent. Hence, the focus of this paper is to question the effectiveness of information use by farmers in India.

Theoretically, information improves the production process by increasing its efficiency, higher efficiency would ultimately lead to higher productivity and thus, better farm outcomes. Therefore, using technical efficiency as a farm outcome is justified when studying the impact of information here. This paper calculates efficiency using a novel technique developed by Cherchye et.al., (2013) and explores the translation of the benefits of information use in terms of higher efficiency gains in farm production using propensity score matching technique. The study finds that users of information have a slightly higher efficiency than non-users but the effects greatly differ across channels of dissemination of information. Private channels have a higher average efficiency than public as well as they have a larger and significant impact. Overall, there seems to be a source effect at work which dampens the true effect of information which indicates that value of the information largely depends on the provider.

Having given a brief background in this section, this paper briefly alludes to the role of information in agriculture and the concept of technical efficiency in section 2. Section 3 elaborates on the data, method and variables used in this study and section 4 discusses the results. The observations and concluding remarks are summarised in section 5.

2. Role of information, impact on agricultural performance and technical efficiency

Role of information

Productivity gains can be achieved through optimum and correct use of technology and inputs which in turn require information. Information helps in accelerating agricultural development by providing the technical know-how and knowledge on different aspects of cultivation like improved practices, inputs and efficient production methods as well as post-harvest management and marketing (Feder and Slade, 1984; Bertolini, 2004, 2006; Hudson, 1991; Lio & Liu, 2006; Palaskas et.al., 1997; Poole & Kenny, 2003; Sarahelen & Sonka, 1997).

Theoretically, neo-classical economics eliminates inefficiency by assuming perfect and costless information, a condition not met in the real world (Knight, 1921). In reality, systems tend to be inefficient and use of information leads to higher technical efficiency¹ provided agents have the capability to access and adopt it. However, ability to process and use information varies across individuals resulting in different outcomes (Simon, 1959). Many empirical studies have argued that knowledge and information are the most important factors for accelerating agricultural development through appropriate

production planning, improved agronomic practices, acquisition of modern inputs, and improved marketing and distribution².

Impact of information

The pioneering studies on the link between information and agricultural performance are offered by Birkhaeuser et al. (1991) and Feder et al. (1999). Studies have used both parametric and non-parametric approaches to isolate the effect of information on agricultural performances. For example, Godtland et al. (2004) estimates a 32 percent increase in income for the participants in farmer field schools of potato farmers in the Peruvian Andes while Davis et al. (2010) found that East African participants in the farmer field schools could realize a 61 percent increase in income. Few studies from India also have assessed the impact of information. Goyal (2010) finds that soybean farmers in the state of Madhya Pradesh have better access to market price information (through the Internet) and achieve 1–5 percent higher prices. Birthal et al (2015) found that users of information in India, on an average, realise a 12 percent higher net returns than non-users.

Again, there are studies identifying information as one of the key factors in increasing efficiency. Some of these identify the factors determining efficiency³ while others specifically see the impact of information on efficiency. Salam and Phimister (2015) find empirical evidence of a significant and positive relationship between farmer ability to access information and farm efficiency of small-scale farmers in Uganda and Aker and Fafchamps (2010) find mobiles are useful in Niger for accessing information. Similarly, the World Bank (2012) finds that access to the internet raises the efficiency of existing processes and makes new production processes possible. Improved access to information could also have more direct efficiency effects associated with cost effective access to agricultural inputs as well as improved managerial practices and farm coordination (De Silva and Ratnadiwakara, 2008) for gherkin farmers in Sri Lanka and for Kerari fishermen in India (Jensen, 2007).

There is also a huge diversity in findings on the impacts of information from different channels on farm outcomes. While very large impacts, as in Davis et al. (2010) for Kenya, Tanzania, and Uganda, Camacho and Conover (2011) and Fafchamps and Minten (2012)⁴ do not find significant impacts in Colombia and Maharashtra, respectively. Again, some studies find moderate to low effects like Birthal, et.al. (2015 and Goyal (2010). Thus, it is difficult to conclude whether it is just the “source effect” or the “true effect” of information on farm outcomes. Source effect relates to the efficacy of some channels of information and lack of it in other cases, whereby information could be useful (the true effect), depending on the source dispensing it.

Several studies, some of which are noted above, have looked into the impact of information either from a specific source (like ICT, extension, mobile phones,

radio etc) and/or a specific kind of information like prices of specific inputs, output, production advice etc on farm outcomes. Few studies like Birtal et.al., (2015) look into several information sources jointly but they do not study the impact on farming efficiency. An attempt is made here to bridge this gap since, theoretically information is expected to increase the efficiency of production and thereby improve productivity and farmers' condition.

Technical efficiency

Central to economic theory is the concept of efficiency. In neo-classical economics, the production frontier is defined as the locus of all efficient points of production, that is, points yielding the maximum output for a given quantity of inputs and technology. Hence, inefficient behaviour is assumed away in conventional economic theory, by using a production function in which first-order and second-order optimizing conditions are satisfied. However, the real-world scenario is very different from the theoretical postulations and inefficiency seems to exist in almost all economic activities. It can be seen that firms using identical inputs in same quantity fail to produce equal amounts of output. This is also true for farmers using same technology and resources but producing different quantities of output. In a theoretical sense, any point lying below the production frontier is an inefficient point and the amount by which it lies away from the frontier is a measure of inefficiency (Forsund et al, 1980).

When we talk about the technical efficiency of a producer, in this case, efficiency of a farmer, we mean a comparison between the actual output (input(s)) of the producer and the optimal output (input(s)), given the technology. Thus, efficiency can be a comparison between the minimum inputs required and the actual inputs used to produce the output or, the maximum output attainable compared to the actual level given the inputs or, a combination of the two (Fried, Lovell and Schmidt, 2005). The most widely used measure of degree of efficiency in a multiple input-output setting is the Farrell (1957) measure, more commonly known as the Farrell efficiency. It defines efficiency as the maximum possible proportional reduction in all inputs to produce a given level of output (input efficiency) or the maximum possible proportional increase in the outputs given the level of inputs (output efficiency) respectively. The next section discusses the method applied to calculate technical efficiency and then estimate the impact of use of information on it.

3. Data and method of analysis

The Situation Assessment Survey of Agricultural Households in India, a decadal survey, conducted by National Sample Survey Organisation (NSSO), published in 2015, is used to carry out the analysis. The data captures various socio-economic aspects of agricultural households and farming. The survey takes into account the major crops grown by each household and their corresponding inputs. For any household, details of a maximum of four major

crops are recorded. For each crop the area on which it is grown and the expenditure for its seeds are recorded. Unlike the last round (59th Round, 2002-03), the other inputs like fertilisers, manures, plant protection chemicals, diesel, electricity, human labour, animal labour, irrigation and other miscellaneous items are recorded jointly for all the crops for each household. The details of the crops grown by households in the first visit are used to calculate technical efficiency and household, farm and farmer characteristics derived from the data are used to estimate the impact on efficiency.

3.1 Measuring technical efficiency

Since, optimal behaviour is a theoretical concept, in practice, efficiency of individual firms is measured relative to the best practice, and hence, in reality we always measure *relative efficiency* rather than absolute efficiency. This is termed as benchmarking. The basic work on efficiency measurement was propounded by Koopmans (1951) and Debreu (1951) and a huge set of literature on estimating production/cost frontiers has developed on its basis. Empirical research on efficiency was carried out by econometricians by average production functions rather than formulating the frontier. However, the pioneering work of Farrell (1957) is the main starting point for estimating frontiers and measuring efficiencies.

The most common tools to calculate efficiency is Data Envelopment Analysis⁵ (DEA, henceforth) and Stochastic Frontier Analysis⁶ (SFA, henceforth). DEA is a non-parametric deterministic frontier model which uses no functional form to estimate the frontier and is very appealing due to the requirement of very few assumptions. Hence, it is more flexible and adapts closer to the data. However, it can be sensitive to extreme values and outliers which can be otherwise addressed through robustness checks. SFA however, assumes a functional form in estimating the efficiency scores and hence, bound by stricter conditions. Given, the advantages of DEA, it is used here to calculate efficiency. Below DEA is discussed briefly.

Data envelopment analysis

DEA is a mathematical programming technique to estimate best-practice production frontiers and then calculate the efficiency of different decision-making units (farm-households in this case), relative to that best frontier. DEA is constructed on the backdrop of production theory and that decision-making units (DMUs) have a common underlying technology T which is given as,

$$T = \{(x, y) \in \mathbb{R}_+^m \times \mathbb{R}_+^n | x \text{ can produce } y\} \quad (1)$$

Here, K farms use m inputs ($x_i, i=1, 2, \dots, m$) to produce n outputs ($y_j, j=1, 2, \dots, n$). The inputs belong to a set of non-negative real numbers, $\mathbb{R}^m$ and the outputs belong to a set of non-negative real numbers $\mathbb{R}^n$.

Since, the production technology is unknown in reality; DEA constructs it on the basis of existing cross-sectional data on actual production activities using the minimal extrapolation principle. The principle extracts the smallest subset from $\mathbb{R}^m \times \mathbb{R}^n$ containing the data based on the assumptions of free disposability and convexity.⁷ Hence, the technology estimated through this principle is used as a proxy for the actual (unknown technology) and existing observations are compared to this frontier to yield relative efficiency scores. Thus, the principle of minimal extrapolation combined with Farrell's notion of efficiency generates the notion of mathematical programming used in DEA to calculate efficiency.

Input-oriented technical efficiency (E) is defined as the maximum possible proportional reduction of all the inputs (x) that still allows the farm to produce y , and TE for the farm o under variable returns to scale (VRS) can be expressed as

$$E^o = ((x^o, y^o); T^*) = \min \{E > 0 \mid (Ex^o, y^o) \in T^*\} \quad (2)$$

Where,

$$T^* = \{(x, y) \in \mathbb{R}_+^m \times \mathbb{R}_+^n \mid \exists \lambda \in \Lambda(\text{vrs}): x \geq \sum_{k=1}^K \lambda^k x^k, y \leq \sum_{k=1}^K \lambda^k y^k\} \quad (3)$$

$$\text{and,} \quad \Lambda^k(\text{vrs}) = \{\lambda \in \mathbb{R}_+^K \mid \sum_{k=1}^K \lambda^k = 1\} \quad (4)$$

λ^k is the weight assigned to the k^{th} farm. Farms with $E=1$ are efficient and operate on the frontier and farms with $E < 1$ are inefficient, that is to say that farther a farm's efficiency score is from 1, lower is its efficiency.⁸

The data used here is characterised by multiple outputs, joint inputs and output-specific inputs as already mentioned earlier. Given the nature of the data, standard DEA method will not yield the best results. To overcome this problem, the study uses the method developed by Cherchye, et.al (2013) to calculate efficiency of DMUs specifically to address the issue of DEA calculation in the presence of **multiple outputs, joint inputs and output-specific inputs**.

This approach is superior to the existing methods because first, it explicitly recognizes that each different output is characterized by its own production technology and simultaneously accounts for interdependencies between

different output-specific technologies. Second, including information on allocation of output-specific inputs substantially increases the discriminatory power of efficiency measurement and hence this method has more power to identify inefficient production behaviour. In turn, this should lead to more actions for efficiency improvement and, consequently, higher realized cost reductions.

This study computes input-oriented technical efficiency of agricultural households under variable returns to scale using the codes created by the authors in the MATLAB software.⁹ The assumption of variable returns to scale gives greater flexibility to the data as compared to constant or decreasing returns to scale (Wadud and White, 2010). Efficiency scores are calculated under the assumptions of convexity and monotonicity.

Input oriented technical efficiency is computed as follows.

$$\hat{E} = \min_{\theta_t \geq 0, \lambda^m \geq 0} \theta_t \quad (5)$$

Subject to

$$\forall m: \sum_{s \in \Omega^m} \lambda^m Q_{st} \leq \theta_t Q_{st} \quad (\text{Joint Inputs}) \quad 5(a)$$

$$\forall m: \sum_{s \in \Omega^m} \lambda^m q_{st}^m \leq \theta_t q_{st}^m \quad (\text{Specific Inputs}) \quad 5(b)$$

$$\forall m: \sum_{s \in \Omega^m} \lambda^m = 1 \quad (\lambda^m \text{ is the weight of each DMUs}) \quad 5(c)$$

3.1.1 Variables used to calculate technical efficiency

To calculate technical efficiency, the output variable used is the sum of the value of crops produced by each household. The input variables are of two types – output-specific like land and expenditure on seed and, joint inputs which is the sum of expenditure on labour, natural and chemical fertilisers, fuel, electricity, irrigation and miscellaneous items. The variables used to compute technical efficiency are listed in table 1 below.

Efficiency is calculated across 15 agro-climatic zones separately as identified by the Planning Commission of India (1989)¹⁰. Calculating efficiency for each zone helps to control the heterogeneity in terms of cropping pattern and differences in technology arising from differences in climate, geography and topography. Table 2 details out the zones and their composition.

Table 1: Variables Used for Calculating Technical Efficiency

Output (Rs.)	Values of crops produced by each household (maximum four crops)
Output-Specific Inputs	
Land (Hectares)	Land use for cultivating each crop
Seed (Rs.)	Expenditure on seeds for each crop
Joint Inputs	
Labour (Rs.)	Expenditure on labour
Fertilisers (Rs.)	Expenditure on fertilisers, manures and plant protection chemicals
Energy (Rs.)	Expenditure on diesel, electricity and irrigation
Others (Rs.)	Expenditure on machinery, repairing and miscellaneous things

Table 2: Agroclimatic Zones

Zones	Composition
1. Western Himalayan Region	Jammu and Kashmir, Himachal Pradesh and Uttarakhand
2. Eastern Himalayan Region	7 North Eastern States and 3 northern districts of West Bengal (CoochBehar, Jalpaiguri and Darjeeling)
3. Lower Gangetic Plains	West Bengal except 3 above districts and Purulia
4. Middle Gangetic Plains	Eastern Uttar Pradesh and Bihar
5. Upper Gangetic Plains	Western Uttar Pradesh
6. Trans Gangetic Plains	Punjab, Haryana and Ganganagar district of Rajasthan
7. Easter Plateau and Hills Region	Chhattisgarh, Jharkhand, Western Orissa, Purulia, parts of Madhya Pradesh and Maharashtra
8. Central Plateau and Hills Region	Parts of Rajasthan, Madhya Pradesh and South Western parts of Uttar Pradesh
9. Western Plateau and Hills Region	Rest of Madhya Pradesh and non-coastal Maharashtra
10. Southern Plateau and Hills Region	Non-coastal Andhra Pradesh (undivided), Tamil Nadu and Karnataka
11. East Coast Plains and Hills Region	Coastal Andhra Pradesh (undivided), Pondicherry, Orissa and Tamil Nadu
12. West Coast Plains and Hills Region	Goa, Kerala, coastal Karnataka, Maharashtra and western hilly parts of Tamil Nadu
13. Gujarat Plains and Hills Region	Gujarat, Dadra and Nagar Haveli and Daman and Diu
14. Western Dry Region	Rest of Rajasthan
15. Island Region	Lakshadweep Islands, Andaman and Nicobar Islands
<i>Source: Constructed from various government publications on the composition of the 15 agro-climatic zones of India</i>	

In each zone, major crops are identified on the basis of their frequency of cultivation. Table 3 below gives the details of the crops grown in each zone.

Zone 15 is excluded here because it consists of island regions of Lakshadweep and Andaman and Nicobar Islands and has very few observations. To minimize the loss of observations, crops are grouped under broad categories like pulses, cereals, vegetables, fodder crops and so on such that the efficiency scores can be identified as representative scores of the zone..¹¹

Table 3 below lists the crops and categories used for our analysis. After removing the observations with infrequent crops, plantation crops, missing observations on land used, seed expenditure and zone 15, a total of 20149 households are available for analysis. Paddy is grown extensively in all the zones except zone 14 and takes the largest share among all crops.

Table 3: Major Crops grown in each Agroclimatic Zone

Zones	Crops	No. of Households
Zone 1	Paddy, Maize and Fodder Crops	698
Zone 2	Paddy, Maize and Leafy vegetables	4746
Zone 3	Paddy and Jute	1606
Zone 4	Paddy, Maize, pulses and Fodder Crops	2198
Zone 5	Paddy, bajra, maize, pulses and fodder crops	1132
Zone 6	Paddy and Cotton	685
Zone 7	Paddy, Maize and Oilseeds	2030
Zone 8	Paddy, Maize, pulses and Oilseeds	1095
Zone 9	Paddy, Jowar, Maize, Pulses, Soyabean, Cotton	1715
Zone 10	Paddy, Jowar, Maize, Pulses, Groundnut, Cotton	1503
Zone 11	Paddy, Groundnut, Pulses, Cotton	1390
Zone 12	Paddy, Banana, Cassava, Tubers	360
Zone 13	Paddy, coarse cereals, pulses, Groundnut and cotton	725
Zone 14	Bajra, pulses, fodder crops	266
Total		20149
<i>Source: Calculated using NSSO 70th Round on Situation Assessment Survey of Agricultural Households (2015)</i>		

3.2 Estimating impact of information on technical efficiency

The treatment here is the use of information which is a dummy variable, I , denoted by 1 if the household has used information and 0 otherwise. The outcome variable, TE , is technical efficiency of agricultural production. Assuming TE is a linear function of the treatment dummy and a vector of explanatory variables (X), the equation can be written as

$$TE = \delta I + \gamma X + \epsilon \quad (6)$$

δ and γ are vectors of parameters to be estimated, and ε is an error term. The impact of information on TE is measured by the parameter δ . However, δ will accurately measure the impact if households are randomly assigned to user or non-user groups (Stefanides & Tauer, 1999; Faltermeier & Abdulai, 2009). Use of information is not randomly assigned, farmers themselves decide whether to use information or not; thus, there is self-selection. In this case, an OLS estimation of Eqn. (6) does not account for this self-selection which may lead to biased results.

One of the standard approaches for dealing with the problem of self-selection in quasi-experimental settings is the instrumental variable (IV) method. However, selection of unobservables in this method is done by imposing distributional and functional form assumptions, such as linearity on the outcome equation and extrapolating over regions of no common support, where no similar user and non-user observations exist. The evidence from Heckman, Ichimura, Smith, and Todd (1998), Dehejia and Wahba (2002), and Smith and Todd (2005) suggest that avoiding functional form assumptions and imposing a common support condition can be important for reducing selection bias. Moreover, the IV approach crucially depends on the availability of valid instruments, which is a challenge in many empirical analyses (Angrist & Krueger, 2001) like here.

Hence, this study uses propensity score matching (PSM) method which takes into account the problem of self-selection and solves for the impact of information use on technical efficiency of agricultural production. PSM does not require linearity, or parametric or distributional assumptions, and it also does not require exogeneity of covariates to identify the causal effect of interest (Diagne & Demont, 2007; Heckman & Vytlacil, 2007).

Here adoption of information is not a random assignment but farmers self-select to adopt or opt out. To understand the impact of information use, we have to estimate the difference in the outcome of the treated household and the outcome of the same household had it not been treated. This is known as the Average Treatment Effect (ATE). To ensure that treatment effect is identified in quasi-experimental settings, it is important to address the selection bias through two main identifying conditions, together called “strong ignorability” assumption by Rosenbaum and Rubin (1983).¹²

First is the Conditional Independence Assumption (CIA, also known as unconfoundedness) which says that the potential outcome (here, technical efficiency) is independent of treatment assignment (to use or not to use information) given that the set of observable covariates are not affected by treatment. This implies, that selection is solely based on observable characteristics and that all variables that influence treatment assignment and potential outcomes simultaneously are observed by the researcher.

Second is the Common Support or Overlap condition which suggests that none of the given observable characteristics should predict D perfectly. It ensures that persons with the same observable characteristics have a positive probability of being both participants and non- participants (Heckman, LaLonde, and Smith, 1999).

The choice of covariates is grounded in theory or in stylised facts. For example, we see from the above discussed literature that use of information has been found to be correlated with farm characteristics, household's socio-economic characteristics and farmer's demographic characteristics like age, education and sex among others. The PSM estimator of ATT is given as

$$ATT_{PSM} = E_{P(X)|I=1} \{ E[TE(1) | I = 1, P(X)] - E[TE(0) | I = 0, P(X)] \} \quad (7)$$

This gives the mean difference in outcomes over the common support, appropriately weighted by the propensity score distribution of participants. In practice, the true propensity score is unknown, and is estimated using a logit or probit model. This study uses a logit model with the covariates displayed in the next section in Table 4.

The validity of this analysis crucially rests on the untestable assumption of CIA, that is the set of observable characteristics alone ensure that potential outcome is independent of treatment assignment and that there is no hidden bias. The first step to justification is the use of covariates extensively used in the literature. The covariates used to undertake matching are indicators of economic status, human capital, and region fixed effects. Nevertheless, it is possible that some unobserved characteristics such as attitude towards risk, motivation and skill influence use of information and its impact on efficiency. Education levels, cropping pattern, sex and age of the household head can act as partial proxies to address these. Still, we cannot fully rule out the possibility of hidden bias from these or other unobservables. Therefore, the robustness of the results is checked through sensitivity analyses, both by varying the set of covariates used to calculate the propensity score and by changing different parameters of the matching process. I Sensitivity of the estimated ATT to hidden bias is tested using the Rosenbaum (2002) bounds test. This test suggests how great an effect unobservables would have to have in order to reverse the findings based on matching on observables.¹³

3.2.1 Variables used to estimate propensity score matching

Covariates are chosen from the existing literature and are broadly categorised as farm characteristics, demographic characteristics and household characteristics which covers the socio-economic characteristics of the household. Farm characteristics like the type of crop grown would influence the decision to use of information because non-food crops are generally high risk-high return crops that demand greater information seeking. Farmer

characteristics like human capital is an important determinant of information comprehension and use. Gender is also an important factor in the Indian rural economy in shaping several outcomes. Age can act as a proxy for experience and skill. Household characteristics like land owned, social group and occupation are indicators of socio-economic status which shape the decision to use information as well as their efficiency in cultivation. Caste is an important determinant of social capital and economic status in India (Deshpande, 2001). Apart from that there are regional fixed effects corresponding to the agroclimatic zones as identified in Table 2. Table 4 lists the covariates used in this analysis and provides summary statistics for the outcome variable and covariates by treatment status.

Table 4: Outcome Variable and Covariates used

Variable	Full Sample	Users	Non-Users	Difference
Outcome Variable				
Technical Efficiency	56	58	54	4***
List of Covariates				
Household Characteristics				
Land owned (hectares)	2.4	2.5	2.3	0.2***
Farmers per household	2	2	1	1***
Cultivation as main source of income (%)	76	80	74	6***
NREGA card holders (%)	52	56	50	6***
Religion (%)				
Hindu	78	80	77	3***
Muslims	9	9	8	1***
Christians	8	6	10	-4***
Others	5	5	5	0
Social Group (%)				
ST	24	18	27	-9***
SC	11	10	12	-2**
OBC	37	40	35	5***
General	28	31	26	5***
House Structure (%)				
Kutcha	9	7	10	-3***
Semi-pucca	33	31	34	-3***
Pucca	58	62	55	7***
Type of Ration Card (%)				
No card	12	9	14	-5***
Antyodaya	4	3	4	-1*
BPL	33	31	34	-3***
Others	51	57	48	9***

Variable	Full Sample	Users	Non-Users	Difference
Demographic Characteristics				
Age of head of household (years)	50.7	51.3	50.5	0.8***
Male head of household (%)	93	94	92	2***
Education Level Attained by Head of Household (%)				
Illiterate	33	29	35	-6***
Primary and below	27	27	28	-1
Middle	16	17	16	1***
Secondary	11	13	11	2***
Above Secondary	12	14	10	4***
Farm Characteristics				
Cropping Pattern (%)				
Food crop	60	56	62	-6***
Non-Food crop	10	11	10	1***
Both	30	32	28	4***
Total	20149	7140	13009	
***, ** and * represent significance at 1, 5 and 10 percent respectively Source: Computed from NSSO 70th Round, Situation Assessment Survey of Farmers (2012-13)				

4. Results and discussion

4.1 Efficiency scores

The average input-oriented technical efficiency is at 56 percent, which means that inputs could be reduced by another 44 percent on average to produce the same value of outputs. Table 5 below shows the efficiency score across the agroclimatic zones and their distribution across users and non-users of information. Agricultural zone 2, the Eastern Himalayan Region comprising of the north eastern states is an outlier, registering the lowest efficiency at 22 percent. Although, there is no direct explanation, certain observations need to be highlighted here. This zone comprises of the entire north east region, a geographically uneven landscape with dispersed political disturbance. In terms of crops, beetle nut (trees) is abundantly grown in this region and excluding it from our calculation might have resulted in a lower performance indicator.¹⁴

Average efficiency rises to 66 percent when we remove zone 2 from our calculation. 8 of the 13 remaining zones record an efficiency score of more than 70 percent while 3 others register 60-70 percent. Except for the outlier, the least efficient zones include the economically poorer regions like middle Gangetic Plains comprising of Bihar and eastern Uttar Pradesh operating at an efficiency level of 53 percent and Eastern Plateau and Hills Region which includes

Purulia and drier parts of Chhattisgarh, Jharkhand, Western Orissa, Madhya Pradesh and Maharashtra. Overall, northern states in the fertile Gangetic belts (except the poorer regions of Bihar and eastern U.P), most part of West Bengal in the lower Gangetic belt, north western states with larger land holdings and better irrigation and the southern states show a higher technical efficiency around 70 percent and above.

Table 5: Technical Efficiency across Agroclimatic Zones

Agricultural Zone	Mean TE	Frequency
Western Himalayan Region	0.72	698
Eastern Himalayan Region	0.22	4,746
Lower Gangetic Plains	0.72	1,606
Middle Gangetic Plains	0.53	2,198
Upper Gangetic Plains	0.73	1,132
Trans Gangetic Plains	0.73	685
Easter Plateau and Hills Region	0.52	2,030
Central Plateau and Hills Region	0.70	1,095
Western Plateau and Hills Region	0.68	1,715
Southern Plateau and Hills Region	0.78	1,503
East Coast Plains and Hills Region	0.64	1,390
West Coast Plains and Hills Region	0.64	360
Gujarat Plains and Hills Region	0.79	725
Western Dry Region	0.77	266
India	0.56	20,149
TE=Technical Efficiency Source: Computed from NSSO 70th Round, Situation Assessment Survey of Farmers (2012-13)		

Some descriptive statistics

Table 4 showed the that the users of information have a significantly higher mean efficiency than non-users. Here, we try to get an idea about the distribution of mean technical efficiency across some important characteristics. Land is one of the most important assets in rural India and a crucial determinant of farmers' behaviour. Table 6 shows the mean technical efficiency of agricultural households across land-size holdings, social groups and cropping pattern and also the difference in efficiency between users and non-users for each variable. We find that efficiency is highest for the smallest group with less than 7 percent share; 76 percent for large land holders and 63 percent medium land holders. Efficiency, is below 60 percent for marginal, small and semi-medium households which account for almost 93 percent of the farming households. Users of information have a higher average efficiency than non-users for each land class. However, the difference is not significant for large land holdings which take the smallest share of less than 1 percent of agricultural households.

Caste, broadly captured by social groups is a major factor in India in determining social capital and economic status (Deshpande, 2001 and Kumar, 2013), access to credit and access to information. Social group is comprised of 4 categories - Scheduled Tribes (ST) who are technically not part of the caste-system but have the lowest socio-economic status, Scheduled Castes (SC), lowest in the caste hierarchy; Other Backward Classes (OBC) who make the largest share of farmers and are better off than the SCs, and General, which are the upper castes. In terms of efficiency, STs have the lowest (43 percent) while all the other groups have an efficiency around 60 percent. The difference in mean efficiencies is positive and significant for all the groups except SCs which takes the smallest share in the sample.

Table 6: Technical Efficiency across Land Holding Classes

Variable		Average Technical Efficiency (%)			
Land Holding Classes					
	Share	Full Sample	Users	Non-Users	Mean Difference
Marginal (0-1 hectares)	37	0.58	0.60	0.57	0.03***
Small (1-2 hectares)	32.2	0.53	0.56	0.51	0.05***
Semi-Medium (2-4 hectares)	24	0.54	0.57	0.53	0.04***
Medium (4-10) hectares	6.2	0.63	0.65	0.60	0.05***
Large (> 10 hectares)	0.6	0.76	0.77	0.74	0.03
Social Group					
Scheduled Tribes	24	0.43	0.45	0.42	0.03***
Scheduled Caste	11	0.61	0.60	0.61	-.01
Other Backward Classes	37	0.59	0.61	0.58	0.03***
General	28	0.60	0.62	0.59	0.03***
Cropping Pattern					
Non-food crop	34	0.66	0.70	0.64	0.06***
Food crop	66	0.56	0.58	0.55	0.03***
Source: Computed from NSSO 70th Round, Situation Assessment Survey of Farmers (2012-13)					

Most households grow food crops or a combination of food and non-food crops. 34 percent of the households in the sample grow non-food crops only and their efficiency is 66 percent, 10 percent greater than that of growing food crops. Users of information have a statistically greater efficiency than non-users but users growing non-food crops have an average efficiency of 70 percent while food-crop is 58 percent. By nature, non-food crops generally are high-risk high- return crops while food crops are mainly of subsistence type which might lead to the difference in their average efficiency levels.

4.2 Matching

The coefficients of the logit model are given in Table 7 below. The sign of the coefficients corroborates the raw differences in table 4. The dependent variable is the binary choice between using and not using information. The estimated coefficients are used to predict the respective probabilities of treatment, that is, the propensity score. Figure 1 shows the distributions of these estimated propensity scores, and establishes that there is overlap in the distribution for treatment and control groups. Figure 1(a) shows the distribution of propensity score before matching between treated and control groups while Figure 1(b) shows the distribution after matching the propensity scores of the two groups scores.

Table 7: Estimation of Propensity Score using Logit Model

Variables	Dependent Variable: Used Information Coefficient
Religion (Base=Hindu)	
Muslim	0.11* (0.06)
Christian	-0.35*** (0.08)
Others	-0.40*** (0.09)
Farmers in a household	0.04*** (0.01)
Size of the household	-0.01* (0.01)
Social Group (Base=ST)	
SC	0.20*** (0.06)
OBC	0.36*** (0.05)
General	0.25*** (0.06)
Land Size Holding (Base=Marginal)	
Small	0.24*** (0.04)
Semi-medium	0.47*** (0.04)
Medium	0.62*** (0.07)
Large	0.88*** (0.20)
Primary source of income (Base=Cultivation)	-0.16*** (0.04)
Age of head of household	0.03*** (0.01)
Square of age of head of household	-0.0003*** (7.06e-05)
Gender (Base=Female)	0.08 (0.06)
Structure of House hold (Base=Kutcha)	
Semi-Pucca	0.15** (0.06)
Pucca	0.15** (0.06)
NREGA Card Holder (Base=Yes)	0.1*** (0.04)
Type of Ration Card Held (Base=No card)	
Antyodaya	0.32*** (0.09)
BPL	0.23*** (0.06)
Others	0.40*** (0.05)
Educational Attainment of head (Base=Illiterate)	
Primary	0.13*** (0.04)
Middle	0.25*** (0.05)
Secondary	0.30*** (0.06)
Above Secondary	0.37*** (0.06)
Non-food crop (Base=food crop)	-0.21*** (0.04)
Constant	-2.57*** (0.23)
Zone Fixed Effects	
Yes	
Observations	20,124
Log-likelihood	-12425.46
Robust standard errors in parentheses	
*** p<0.01, ** p<0.05, * p<0.1	

Source: Computed from NSSO 70th Round, Situation Assessment Survey of Farmers (2012-13)

The average treatment effect (ATT) is calculated both for the matched and unmatched households. Table 8 below shows the impact of information on users and also source-wise impact on households.^{15,16} We see that the impact of information is small but positive for users but it largely varies across the sources. To test for hidden bias that makes the treatment endogenous in the presence of unobserved confounding variables, this study uses Rosenbaum bounds method. It is found that when the odds of receiving treatment (using information) due to unobserved pre-treatment differences goes beyond 30 percent ($\Gamma > 1.3$) then the results become sensitive to hidden bias as shown Table 9 below.

The share of users of information is 35 percent and they have an efficiency of 58 percent, 1 percent more than non-users. However, disaggregating impact into public channels, private channels and media, we see a considerable variation. Private channels have the highest impact; users are efficient at 63 percent, 3 percent more than non-users. Also, within private users, progressive farmers, the most common source, used by households, have the highest impact. Users of information from progressive farmers are 10 percent more efficient than non-users.

The impact of media is small and statistically significant at 10 percent only. Users have an efficiency of 56 percent, only 1 percent more significant than non-users. Media, however, has the highest access across all the sources but the lowest use. Media is a human-capital intensive source and scholars like Just, et.al. (2002), Simon (1959), Schultz (1965) argue that human- capital intensive information cannot be comprehended without proper education while informal (private) information which is context-specific and decision-focused (Boehlji, 1998) spreading through oral interaction within a group is easier to comprehend by less educated people.

Table 8: Average Treatment Effect for Users of Information and Users across Sources

Sample	Users (%)	Users	Non-users	S.E.	T-stat
	Use of Information				
Matched	35	0.58	0.57	0.005	2.03**
Unmatched		0.58	0.55	0.005	7.26***
Public Channels (extension agent, <i>Krishi vigyan kendras</i> , agricultural universities, veterinary dept.)					
Matched	15	0.56	0.56	0.005	0.18
Unmatched		0.56	0.56	0.007	0.62
Private Channels (Progressive farmers, NGOs, Private Commercial Agents)					
Matched	21	0.63	0.6	0.006	3.30***
Unmatched		0.63	0.54	0.006	15.14***
Media (Radio/TV/Newspaper/Internet)					
Matched	14	0.56	0.55	0.007	1.79*
Unmatched		0.56	0.56	0.006	0.44
Matched	18	0.63	0.53	0.1	15.7***
Unmatched		0.63	0.54	0.09	13.9***
Matched	29	0.6	0.54	0.005	11.25***
Unmatched		0.6	0.58	0.005	3.32***
Media and Public (formal Source)					
Matched	24	0.56	0.56	0.06	-0.4
Unmatched		0.6	0.58	0.005	0.95
Source: Computed from NSSO 70th Round, Situation Assessment Survey of Farmers (2012-13)					

Table 9: Sensitivity Analysis using Rosenbaum Bounds

Gamma	Maximum P value
1	0
1.1	8.8e-11
1.2	0.0006
1.3	0.0742
1.4	0.9909
1.5	1

More than 60 percent of the heads of households are illiterate, which might have led to lower use of media as well as its weaker impact on technical efficiency. Comparing households that have accessed media and public sources jointly (formal sources) and media with private sources, the effect of the former is 56 percent and not statistically significant while it comes out to be significantly greater among users at 63 percent for the latter (Table 8).

The share of users of public channels and media are similar but the impact of public channels have no statistical significance. However, to conclude that public channels are not useful would greatly undermine their economic significance as explained below.

In most developing economies, information and knowledge on new agricultural technology and practices are a public good and the most common way of disseminating it is through agricultural extension services (Birkhaeuser, Evenson, & Feder, 1991; Dancey, 1993; Dinar, 1996; Umali & Schwartz, 1994). The formal agricultural extension system has been the government's main channel to disseminate the required information and knowledge to the farmers. However, the efficiency of public extension has been constrained by poor infrastructure, reduction of public funds and poor technical background of the employees.¹⁷ Lack of incentives to the agents/employees and improper monitoring among others are major factors in reducing the efficiency of public sources of information (Babu et.al., 2015). Analysing the Situation Assessment Survey of 2003 (NSSO, 59th Round) Adhiguru et al. (2009) found that service delivery by public-sector extension workers was biased against small and marginal farmers, the largest section of Indian farmers. Quality and reliability of public extension was also a major concern (Babu, et.al., 2012).

Although information is generated or transmitted by the government, government policies like Agricultural Technology Management Agency (ATMA) aiming at pluralistic demand-driven (bottom-up) approach towards farmers' need-based information focuses on dissemination using public, private and non-profit organisations. Private channels, especially progressive farmers take the largest share of users of information and their impact is also higher and significant compared to public and media channels. Given the central role of the government in information dissemination and the constraints

faced by the public channels this might suggest a two-step dissemination - progressive farmers and other private sources get the information from public channels (formal sources) and then disseminate it to farmers in their vicinity or community.

Thus, we observe that even though impact of information is positive on users, its impact and magnitude vary a lot across different sources of information. The true effect of information gets dampened by the source effect indicating that the value of information changes across sources. Farmers value information from progressive farmers more than any other sources. One reason might be the demonstration effect, farmers believe what they see. Progressive farmers in the neighbourhood are less risk averse than small and marginal farmers. So, they are generally the first ones to adopt the information while the poorer risk-averse farmers acquire the information from them based on the outcomes. Limited spread of public channels, low literacy among farmers and their poor socio-economic status impedes their reliability on non- private channels. Therefore, the impact of information varies largely across sources. However, the results should not be used to undermine the public channels since the apex entity that generates and disseminates information is the government. It simply suggests further probing into the dissemination pattern because it might be reasonable to argue that the progressive farmers acquire the information from public channels and therefore act as secondary source of information.

Figure 1: Distribution of propensity score of treated and control groups before and after matching

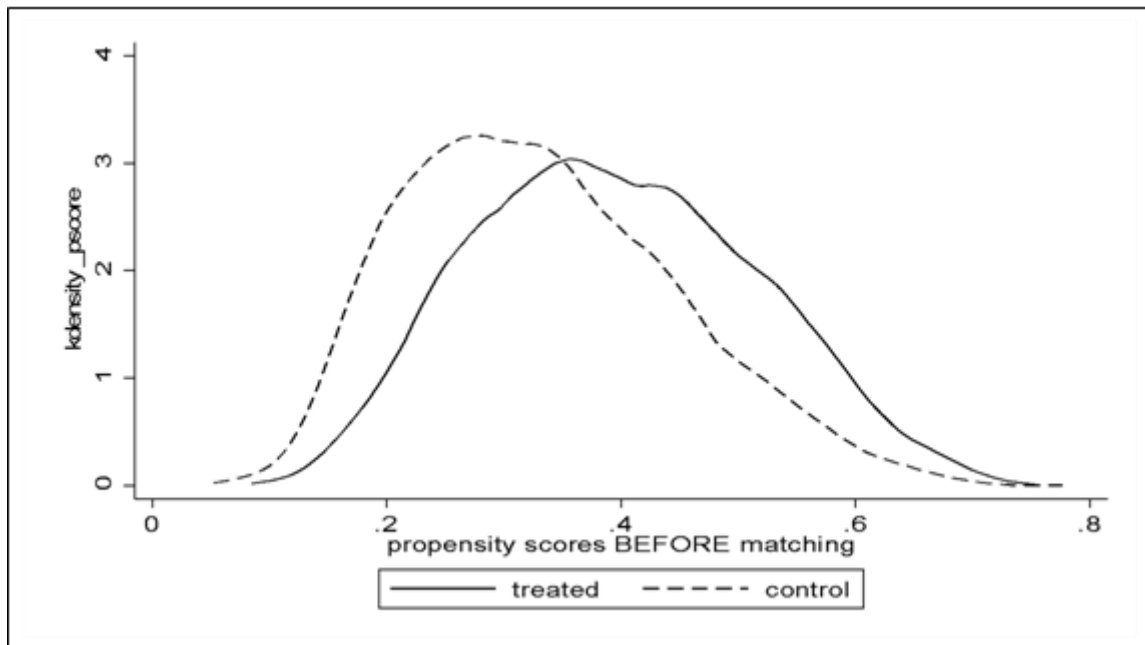


Figure 1(a)- Before matching

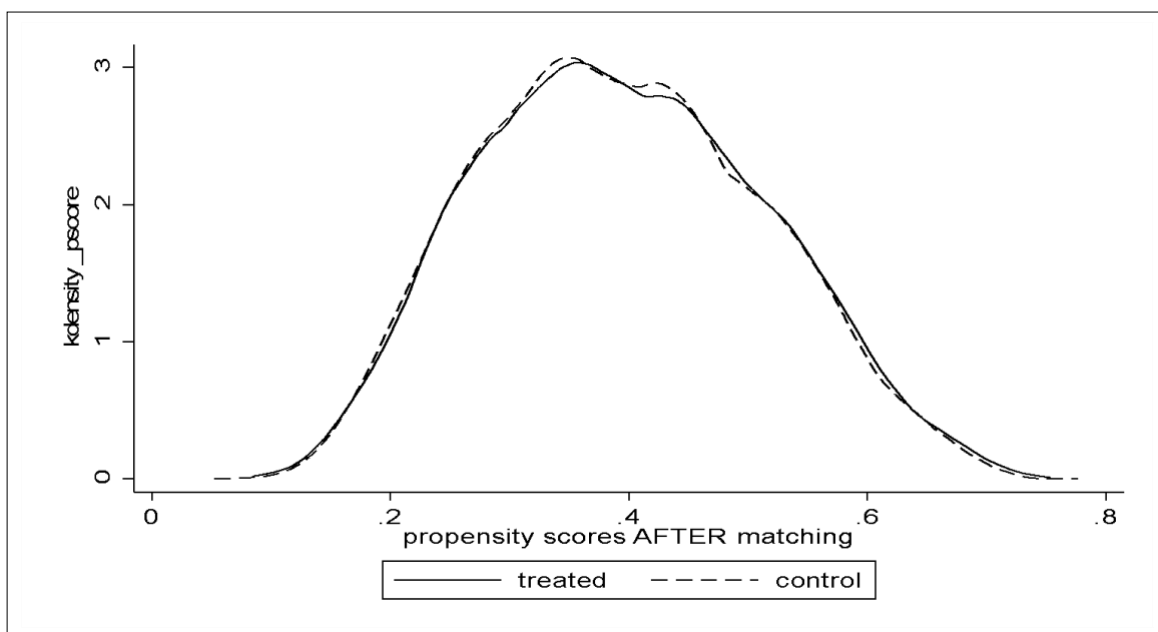


Figure 1(b)- After Matching

5. Conclusion

From a global perspective, increasing the productivity of agriculture, given the limited scope of increasing land under cultivation, is necessary for both poverty reduction and the development of the non-agricultural sector. Agricultural productivity gains, poverty reduction, and the growth of the nonfarm sector are complements. In India more than 60 percent of the population is dependent on agriculture and improving agricultural productivity remains the primary concern of policy makers. This paper has tried to estimate the impact of information use on technical efficiency of crop production by agricultural households in India especially after the introduction of pluralistic and demand-driven extension policies like Agricultural Technology and Management Agency in 2005.

It is found that access to information has stagnated at 41 percent for a decade from 2002-03 to 2012-13. Use is even lower at 35 percent and is lowest for formal sources like public and media while highest for private sources, especially progressive farmers. Using a novel technique to calculate technical efficiency in the presence of multiple outputs, joint inputs and output specific inputs, it is found that average efficiency of farming households is 56 percent and that of users of information is 58 percent; slightly higher than non-users. The impact on users is positive but low suggesting that the true effect of information is dampened by the source effect.

Users of public sources and media have a lower average efficiency than private. Impact is significantly higher for private users as compared to media and public users.

The results direct to the fact that on the demand side, the same information might be valued more when it comes through private sources as compared to public sources. However, that should not undermine the public channels since the government is the main entity that generates and disseminates information. It could be that the progressive farmers acquire the information from public channels and therefore act as secondary source of information. Therefore, the results suggest further probing into the dissemination pattern.

On the supply side literature supports that the public extension is limited in its spread and expertise due to several problems in infrastructure, quality of employees and biasedness against poor farmers. The reliability on progressive farmers and informal sources as a whole seems to be much greater than on formal sources. On the demand side, factors like lack of education of farmers act as a deterrent to using information from formal channels like media. Media is a human-capital intensive source which might be difficult to comprehend without proper education while informal (private) information which is context-specific and decision-focused spreading through oral interaction within a group is easier to comprehend by less educated people. Some of the hurdles to rural welfare are access to credit, infrastructure, farmers' socio- economic conditions and education and these are mostly interlinked with each other. However, a deeper understanding of the reasons for the stagnation of access to information and the variability across sources is required to deliver better extension services to the farmers for higher agricultural gains.

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Appendix

Table A1: ATT for different matching algorithms

Treated	Controls	S.E.	T-stat
Kernel with bandwidth 0.05			
0.58	0.57	0.005	2.03**
Kernel with bandwidth 0.01			
0.58	0.57	0.005	1.80*
Nearest neighbour with 1 neighbour with common support, with replacement			
0.58	0.57	0.007	0.95*
Nearest neighbour with 2 neighbours with common support, with replacement			
0.58	0.57	0.006	1.12**
Nearest neighbour with 3 neighbours with common support, with replacement			
0.58	0.57	0.006	1.07*
Nearest neighbour with 4 neighbours with common support, with replacement			
0.58	0.57	0.006	1.60*
Nearest neighbour with 5 neighbours with common support, with replacement			
0.58	0.57	0.006	1.23**
Nearest neighbour with 6 neighbours with common support, with replacement			
0.58	0.57	0.005	1.36*
Nearest neighbour with 7 neighbours with common support, with replacement			
0.58	0.57	0.005	1.31*
Nearest neighbour with 8 neighbours with common support, with replacement			
0.58	0.57	0.005	1.42**
Nearest neighbour with 9 neighbours with common support, with replacement			
0.58	0.57	0.005	1.40*
Nearest neighbour with 10 neighbours with common support, with replacement			
0.58	0.57	0.005	1.39**
Caliper matching within 0.2 with common support			
0.58	0.57	0.005	2.13**
Radius matching with common support with 0.05 caliper			
0.58	0.57	0.005	2.19**
Abadie and Imbens 2006 method only with Nearest Neighbour (2 neighbours)			
0.58	0.57	0.006	1.16*

Table A2: Estimation of Covariate Balancing

Variable	Treated	Control	Reduction in bias (%)	t-value	p>t			
Muslim	.09199	.0929	91.8	-0.19	0.852			
Christian	.05665	.05604	98.6	0.16	0.874			
Others	.04684	.04476	41.8	0.59	0.552			
Farmers in a household	2.463	2.4583	94.9	0.20	0.841			
Size of the household	5.4607	5.4595	97.0	0.03	0.979			
SC	.10531	.10559	97.4	-0.05	0.957			
OBC	.39896	.40272	92.2	-0.46	0.647			
General	.31272	.30718	89.3	0.71	0.475			
Marginal	.32604	.33102	16.2	-0.63	0.527			
Small	.2799	.27763	96.7	0.30	0.762			
Medium	.08344	.0781	83.6	1.17	0.242			
Large	.00982	.00819	69.1	1.03	0.302			
Cultivation as main source of income	.20053	.20022	99.4	0.05	0.962			
Age of head	51.258	51.231	96.5	0.12	0.901			
Square of age of head	2793.8	2791.7	96.6	0.09	0.925			
Female head	.93774	.93789	99.1	-0.04	0.969			
Semi-Pucca	.30809	.31166	89.7	-0.46	0.645			
Pucca	.62025	.61734	95.7	0.36	0.721			
NREGA Card Holder	.56177	.55767	93.5	0.49	0.621			
Antyodaya	.03267	.03387	71.4	-0.40	0.690			
BPL	.30459	.30845	89.3	-0.50	0.617			
Others	.57047	.56681	95.9	0.44	0.659			
Primary	.27149	.2709	89.6	0.08	0.937			
Middle	.17193	.17171	98.4	0.03	0.973			
Secondary	.12845	.13106	88.6	-0.46	0.644			
Above Secondary	.13462	.13186	89.6	0.49	0.627			
Non-food crop	.56191	.56695	91.9	-0.61	0.544			
Eastern Himalayan Region	.20418	.20481	98.7	-0.09	0.926			
Lower Gangetic Plains	.10069	.09838	92.9	0.46	0.645			
Middle Gangetic Plains	.08344	.08509	95.8	-0.36	0.722			
Upper Gangetic Plains	.06156	.0634	77.9	-0.45	0.651			
Trans Gangetic Plains	.05006	.04741	89.3	0.73	0.462			
Easter Plateau and Hills Region	.09816	.099	80.2	-0.17	0.868			
Central Plateau and Hills Region	.04684	.04678	99.5	0.02	0.986			
Western Plateau and Hills Region	.07559	.07859	79.9	-0.67	0.501			
Southern Plateau and Hills Region	.10237	.1029	98.8	-0.10	0.917			
East Coast Plains and Hills Region	.07615	.07891	74.8	-0.62	0.537			
West Coast Plains and Hills Region	.01599	.01618	93.4	-0.09	0.927			
Gujarat Plains and Hills Region	.05006	.04535	78.3	1.32	0.187			
Western Dry Region	.00575	.00475	91.4	0.82	0.411			
Ps R2 LR chi2 p>chi2 MeanBias MedBias B R								
%Var	0.000	8.21	1.000	0.7	0.7	4.8	1.16	50

* if B>25%, R outside [0.5; 2]

The standardised percentage bias is the percentage difference of the sample means in the treated and non- treated (full or matched) sub-samples as a percentage of the square root of the average of the sample variances in the treated and non-treated groups (formulae from Rosenbaum and Rubin, 1985). Rubin (2001) recommends that B be less than 25 and that R be between 0.5 and 2 for the samples to be considered sufficiently balanced. An asterisk is displayed next to B and R values that fall outside those limits. The null hypothesis is the equality of the values of each variable between treated and control for the matched data.

Table A3: Estimation of Propensity Score by Source of Information using Logit Model

Variables	Dependent Variable Used Public		Dependent Variable Used Private		Dependent Variable Use Media	
Religion (Base=Hindu)						
Muslim	-0.206**	(0.0838)	-0.0442	(0.0724)	0.199***	(0.0746)
Christian	-0.198**	(0.0974)	-0.373***	(0.110)	-0.226**	(0.103)
Others	-0.128	(0.103)	-0.425***	(0.114)	-0.481***	(0.117)
Farmers in a household	0.0568***	(0.0183)	0.0310*	(0.0169)	0.0244	(0.0188)
Size of the household	-0.0127	(0.00954)	-0.0149*	(0.00840)	-0.00489	(0.00953)
Social Group (Base=ST)						
SC	0.112	(0.0850)	0.186**	(0.0747)	0.177*	(0.0935)
OBC	0.245***	(0.0669)	0.338***	(0.0599)	0.458***	(0.0733)
General	0.199***	(0.0733)	0.269***	(0.0668)	0.392***	(0.0782)
Land Size Holding (Base=Sub-marginal)						
Marginal	0.282***	(0.0537)	0.235***	(0.0477)	0.132**	(0.0544)
Small	0.471***	(0.0584)	0.462***	(0.0525)	0.310***	(0.0594)
Medium	0.691***	(0.0866)	0.546***	(0.0800)	0.373***	(0.0915)
Large	0.838***	(0.217)	0.478**	(0.209)	0.942***	(0.212)
Primary source of income (Base=Cultivation)	-0.172***	(0.0545)	-0.101**	(0.0480)	-0.168***	(0.0551)
Age of head of household	0.0604***	(0.0107)	0.0125	(0.00888)	0.0344***	(0.0104)
Square of age of HoH	-0.00054***	(0.0001)	-	(8.37e-05)	-	(9.6e-05)
Gender (Base=Female)	0.0870	(0.0849)	0.0531	(0.0749)	0.103	(0.0901)
Structure of Household (base=Kutcha)						
Semi-Pucca	0.226**	(0.0879)	0.0948	(0.0724)	0.0312	(0.0861)
Pucca	0.366***	(0.0862)	-0.0279	(0.0706)	0.0779	(0.0841)
NREGA Card Holder (Base=Yes)	-0.00884	(0.0472)	0.00694	(0.0420)	0.287***	(0.0487)
Type of Ration Card Held (Base=No card)						
Antyodaya	0.189	(0.139)	0.210*	(0.115)	0.239*	(0.137)
BPL	0.384***	(0.0805)	0.101	(0.0702)	0.244***	(0.0793)
Others	0.461***	(0.0760)	0.365***	(0.0661)	0.284***	(0.0732)
Educational Attainment of head (Base=Illiterate)						
Primary	0.194***	(0.0559)	0.0881*	(0.0486)	0.304***	(0.0597)
Middle	0.305***	(0.0658)	0.113*	(0.0583)	0.476***	(0.0685)
Secondary	0.363***	(0.0720)	0.0724	(0.0658)	0.719***	(0.0725)
Above Secondary	0.445***	(0.0750)	0.0725	(0.0675)	0.802***	(0.0747)
Non-food crop (Base=food crop)	-0.0787*	(0.0457)	-0.162***	(0.0418)	-0.179***	(0.0466)
Constant	-4.241***	(0.325)	-4.138***	(0.330)	-3.818***	(0.320)
Zone Fixed Effects	Yes		Yes		Yes	
Observations	20,124		20,124		20,124	
Log Likelihood	-8172.57		-9622.37		-7872.48	

Source: Computed from NSSO 70th Round, Situation Assessment Survey of Farmers (2012-13)

Notes

-
- ¹ See Muller (1974) and Shapiro and Muller (1977)
 - ² See Poole and Kenny (2003), Bertolini (2004) and Lio and Liu (2006)
 - ³ Muller (1974); Kalirajan and Shand (1986); Fan (1991 & 2000); Coelli and Battese (1996), Kumbhakar (2000),
 - ⁴ Fafchamps and Minten (2012) do not find a significant impact from information obtained through mobile phones, either on the quality of farm produce or on the prices in Maharashtra.
 - ⁵ Charnes, Cooper and Rhodes (1978), and Deprins et al (1984)
 - ⁶ Aigner et al (1977), Battese and Coelli (1992), Coelli et al (1998a)
 - ⁷ Free disposability refers to the fact that more inputs can be used to produce less output and convexity means that a weighted average of two production points is also a feasible point
 - ⁸ It must also be noted that efficiency estimates under DEA are scale independent with respect to measurement of inputs and outputs. Thus, the results do not change with any positive linear transformation of the inputs and/or outputs. This means that one can use monetary values of the variables instead of their physical values (Bogetoft and Otto, 2011).
 - ⁹ Refer to the article for further details.
 - ¹⁰ Khanna (1989) identified 15 resource development regions in the country - 14 in the main land and one in the islands of Lakshadweep and Andaman Nicobar Islands.
 - ¹¹ A variety of crop combinations and categories were tried before finalising the present categories based on their relative frequency of occurrence. The results remain qualitatively same, but this minimises the loss of observations
 - ¹² Estimation of average treatment effects requires that the treatment effect for each individual *i* is independent of treatment participation of other individuals ('stable unit-treatment value assumption'). In randomised experiments the treatment effect is identified due to the random assignment of treatment.
 - ¹³ For more details see the bounding approach proposed by Rosenbaum (2002)
 - ¹⁴ For the sake of comparability across crops this study has excluded crops that require more than one season (6 months to grow). Hence, all kinds of trees and plantation crops are dropped from the analysis. Further, output and expenditure should be for the period under consideration (here, 6 months corresponding to Visit 1 of the survey) and trees do not come under this definition. Separate research is required to understand the poor performance of this zone which is currently not possible with the data in hand.
 - ¹⁵ The results displayed are done using kernel matching with 0.05 bandwidth. For robustness matching is done with bandwidth 0.01 and using other algorithms like nearest neighbour (1 to 10), caliper and radius matching see Table A1 in Appendix). The choice of the matching algorithm can be important in small samples (Heckman, Ichimura, and Todd, 1997), where there is typically a trade-off between bias and variance but as sample size grows, all the PSM estimators yield the same results asymptotically since they all become closer to comparing only exact matches Smith (2000). Since, our sample is substantially large, we do not see any substantial difference in the results from different algorithms.
 - ¹⁶ The covariate balancing table and the propensity score estimates across sources in given in Appendix (see Tables A2 and A3)
 - ¹⁷ See Sulaiman and Van den Ban (2003), Birnar and Anderson (2007), Ferroni and Zhou (2012) for more details on the public extension system in India.

Does innovation drive up income's inequalities in Africa?

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Abstract

This paper empirically analyzes, for the first time in Africa, the impact of innovation on income inequality over the period 2000-2021. Four indicators of income inequality are used, from the World Development Indicators (WDI), the World Inequality Database (WID), and the Standardized World Income Inequality Database (SWIID), respectively; and the measure of innovation is the number of patents (resident and non-resident) from the World Intellectual Property Organization (WIPO). Three main results emerge: First, innovation is positively and significantly associated with income inequality at the 1% threshold. Second, access to electricity, trade openness, CO2 emissions, and natural resource rents significantly reduce income inequality, while the opposite is true for government consumption expenditure. Third, the results show a non-linear inverted-U relationship between innovation and income inequality. Thus, there is a threshold above which innovation becomes a factor in reducing income inequality in Africa. Indeed, it is incumbent upon African countries to consider innovation not only as a critical factor in the economic development of nations, but also as a potential vector that can widen the income gap between individuals. A key recommendation would be the establishment of policies for the appropriation and absorption of innovation on the continent.

Keywords: Innovation, Income inequality, Africa

JEL classification: D31, O31, O4, O55

1. Introduction

The rise in income inequality in many countries since 1985, and particularly during the global financial crisis of 2007-2008, has led to a growing public awareness of the causes and consequences of rising inequality and its implications for future growth (Ostry et al., 2014). While Africa has experienced considerable growth since the early 2000s (an annual growth rate of 4.6% according to the World Bank), this growth has not translated into improvements in well-being. Indeed, poverty and inequality continue to characterize the African social system. The continent remains characterized by a deterioration in the quality of institutions, which hinders transaction costs, the protection of property rights, entrepreneurial activities and innovation (Saima, 2015). The coronavirus pandemic (COVID-19), the climate crisis and, since March 2022, the war between Russia and Ukraine have hit the African continent, which was already in a precarious situation. This series of events has exacerbated the inequalities that already existed in Africa and within countries. As an illustration, states with the highest income inequality have a higher number of deaths due to COVID-19 (Oronce et al., 2020). With soaring food prices, unemployment and income inequality are also present. The observation in Figure 1 confirms that Africa is the region of the world where income inequality persists. Without being exhaustive, the literature holds natural factors responsible, because there are regions richer in natural resources (oil, mining, gas) than others (Stiglitz, 2006; Sebri and Dachraoui, 2021), and economic factors, because countries such as Côte d'Ivoire, Mauritius and Rwanda have achieved considerable economic performance over the last decade, lifting millions of people out of extreme poverty, leaving other countries lagging behind. (Förster and Pearson, 2002; Piketty, 2015); and finally competitiveness factors because some countries are more competitive, creative and innovative than others (Waheeduzzaman, 2002; Georgescu and Kinnunen, 2021).

The issue of inequality then represents a universal appeal and is of great importance because high levels of income inequality could weaken the effectiveness of development policies in terms of poverty reduction (Kaulihowa and Adjasi, 2018). It is therefore not surprising that one of the Sustainable Development Goals (SDGs) is dedicated to reducing inequality, via target 10.1 "*reduce income inequality*". Therefore, the field of study continues to attract the attention of economic researchers (Bourguignon and Morrisson, 1990 ; Stiglitz, 2012; Piketty, 2018; Piketty, 2015; Sulemana and Kpienbaareh, 2018; Ongo and Song, 2021), as income inequality rises as a global problem that calls for global and innovative solutions. Today, with innovation being a major concern that affects the economic future and geopolitical influence of countries (Menissier, 2011), both developed and developing economies are promoting innovation to achieve economic and social development, as there is a greater realization that innovation occurs in all areas of the economy and not just in high-tech firms

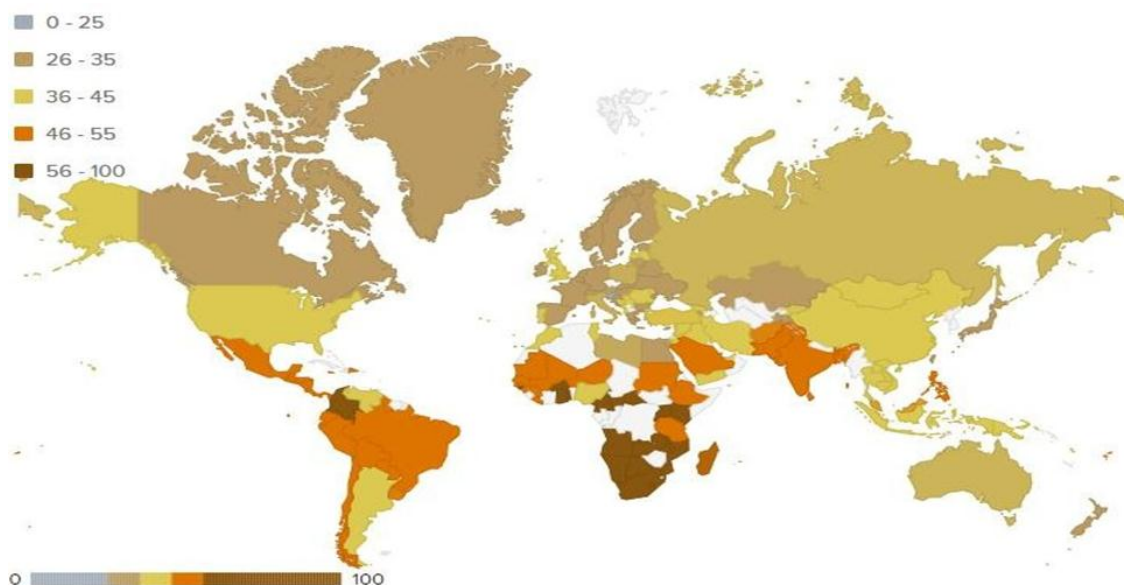
and technology sectors (WIPO, 2019). In this context of globalization, the ability of countries to innovate is a key factor in creating very high value added and increasing economic competitiveness (Atkinson, 2013). If we accept that human development has been stimulated by the evolution of technologies, periods of inequality would also have appeared with the industrial revolution (Kuznets, 1955; Lindert and Williamson, 1985). Indeed, new technologies can lead to serious disadvantages if they exceed the adaptive capacity of a society. In light of this, sustained investment in infrastructure and innovation is a key driver of economic growth, development, and especially the reduction of inequality (Tabrizian, 2019). Moreover, nations that suffer from inequality also have more difficulty than others in achieving economic growth (Cozzens, 2008).

Most studies linking innovation and inequality focus on skill-biased technological change and its effects on employment (Hatz-Hart, 2000; van Reenen, 1996; Faggio et al., 2007; Saint-Paul, 2008), worker income (Butler and Dueker, 1999; Johnson, 1997; Pieroni and Pompei, 2008; Echeverri-Carroll and Ayala, 2009), and different industries (Bertola, 2000; Bertola, Foellmi, and Zweimüller, 2006; Samargandi, 2018). In Africa in particular, therefore, little is known about the role of innovation on income inequality. Given its adverse social situation, Africa faces real economic challenges that can be transformed by technical and technological advances.

The aim of this paper is to analyze the effect of innovation on income inequality in Africa. The contribution of this paper is based on three dimensions. **First**, this paper contributes to the scarce literature that assesses the effect of innovation on income inequality in Africa. Most studies focus on European or North American cities and countries (Butler and Dueker, 1999; Johnson, 1997; Pieroni and Pompei, 2008; Echeverri-Carroll and Ayala, 2009; Lee and Rodriguez-pose, 2013; Tsiachtsiras, 2018; Law et al., 2020). **Second**, this paper mobilizes a sound methodological strategy given the nature of our data. We make use of the new instrumental variables (IV) techniques of endogeneity resolution including kivet (2020), Lewbel two stage least square (Lewbel 2SLS), and Generalised Method of Moments in system (GMMs). The use of four measures of income inequality confirms the validity of our results. In addition, the article analyzes the possible existence of a non-linear effect, but also investigates the mediation of the effect studied by several theoretically referenced variables. **Third**, the results of this paper provide new evidence on the effect of innovation on inequality in Africa. These can potentially be used by governments to make targeted and strategic policy decisions to ensure better ownership of innovation and reduce inequality.

The remainder of the article is organized into four additive sections. Section 2 presents lessons from the literature. Section 3 briefly outlines the different steps of the empirical strategy. Section 4 discusses the results. Finally, Section 5 concludes with policy recommendations.

Figure 1 : Map of world income inequality



Source: UNU-WIDER (2019)

2. Review of the literature

2.1. Theoretical review

Schumpeter (1934) set the milestones in the literature on innovation, for whom innovation is primarily the result of science and technology. He distinguishes five types of innovation. First, product innovation. This first type of innovation includes radical transformations (new product), but also more limited ones ; we then speak of incremental innovation. Second, process innovation, which is based on new production methods, whether in terms of tools, logistics or organizational methods. Third, the exploitation of new markets, including the invention of new ways of selling or promoting a product. Fourth, new ways of offering products to the market. Finally, new ways of organizing firms, which result from regulatory changes through the possibility of forming corporations or opening up a market. The literature on the determinants of income inequality identifies innovation as the main source of imbalances in the structure of labor markets and wages (Antonelli and Gehringer, 2017). Skill-based technological change can work in favor of the most skilled workers by accelerating the substitution of unskilled labor (Acemoglu, 2002). Similarly, high-skilled workers benefit from bonuses and better wages. Thus, the combination of substitution and wage effects exacerbates income inequality (Katz and Murphy, 1992).

Several analyses provide theoretical support for the conjecture that innovation stimulates entrepreneurship but also increases income inequality (Drucker,

2014) in the absence of policy guidance through investment in research and development and human capital formation (Bilbao and Rodríguez, 2004). More recently, developments by Aghion et al. (2019) show theoretically, through a Schumpeterian growth model, that a higher rate of innovation at entry and a higher rate of innovation at exit are associated with an increase in the income share of entrepreneurs, which, assuming that at least some of the highest earners are successful innovators, leads to greater inequality of the highest incomes (Aghion et al., 2019; Jones and Kim, 2018). From the demand side, the literature also analyzes the extent to which inequality can be a barrier to innovation through prices and market size and shape (Foellmi and Zweimüller, 2017; Copulsky, 1976). From the demand side, in a more egalitarian society, innovation becomes more attractive through the incentive to mass produce goods (Napolitano et al., 2022). However, based on sectoral development and localized production systems based on territorial innovation models (industrial districts, innovative environments, new industrial spaces, local production systems, etc.), there may be greater income dispersion in innovative sectors or territories based on decentralized wage structures, irregular systems of labor regulation, or highly variable rates of return for specific innovations (Faggio et al., 2010; Moulaert and Sekia, 2003; Doloreux, 2002; Storper and Scott, 1990).

2.1. Empirical review

From the studies reviewed, we find mixed results on the impact of innovation on income inequality. First, by examining the role of innovation in income inequality in twenty-three developed countries. Three indicators of income inequality are used, namely the Standardized World Income Inequality Database (SWIID), the University of Texas Inequality Project (UTIP), and the Estimated Household Income Inequality (EHII). Using two indicators of innovation, patent applications and patents granted. Using a panel mean group estimate that allows for cross-sectional dependence, Law et al. (2020) find that innovation increases income inequality. They also find that the relationship between innovation and income inequality depends on a country's level of globalization and financial development. They also include interaction terms and find that the interaction between innovation and globalization and the interaction between innovation and financial development increase income inequality. Tang et al (2022) test the effect of technological innovation on income inequality (Gini index) using a sample of 73 countries worldwide. They use quantile regression to test the impact of technological innovation on income inequality. The results show that for most quantiles, the impact of technological innovation on inequality is positive. However, they find that government spending reduces inequality in all quantiles. Similarly, using data on 128 countries from the World Bank and the Global Innovation Index, He (2022) finds strong and high inequality across countries in innovation capacity, innovation sustainability, and benefits from intellectual property.

Second, Aghion et al. (2019) examine the aggregate effect of innovation on top income inequality and social mobility. They use a sample of interstate panel data and U.S. commuting area data. The correlations show a positive relationship between innovation measures and top income inequality. However, these correlations between innovation and general measures of inequality are not significant. Using instrumental variable analysis, they find a relationship between innovation and top income shares. Similarly, Włodarczyk (2017) presents a regression analysis based on measures of innovation capacity (gross domestic expenditure on R&D, number of patent applications, creative economy index) and income inequality (Gini coefficient, top 3 percent and top 1 percent shares of equalized national income). The data sample consists of 30 countries (European Union countries, Iceland, Norway) spread over the study period from 2005 to 2014. The results provide evidence that increasing gross domestic expenditure on R&D as a percentage of GDP tends to increase inequality, while increasing the number of patent applications and the value of the Creative Economy Index have a negative effect.

Third, Çelik and Sayın (2022) examine the causal relationship between technology, innovation, and income inequality in G7 countries over the period 1981 to 2015. They use the Granger panel bootstrap approach. The effect of the aforementioned relationship is analyzed using two different Gini coefficients for pre-tax and post-tax income. The results show that the two-way causality is not detected in the G7 countries, with the exception of France. Moreover, the signs of the relationship differ across countries, with income tax playing an important role in this differentiation. In addition, Liu and Lawell (2015) examine the impact of innovation on income inequality in China based on a sample of available panel data over the period 1995-2011. As a result, they estimate an instrumental variable model. The obtained results show that innovation significantly reduces income inequality in China. The nonlinearity test by innovation squared shows a U-shaped relationship between the level of innovation and the ratio of urban to rural income. It is also noteworthy that both industrialization and urbanization increase income inequality. Kanwal and Eyisi (2022) use annual data for thirty-one frontier markets over a 15- year period from 2003 to 2018. On the one hand, they find a non-significant relationship between income inequality and innovation using a fixed effects panel regression. On the other hand, instrumental variable estimation reveals a significant relationship between measures of innovation and income inequality.

Finally, Hailemariam et al. (2021) examine the main drivers of income inequality in OECD countries based on long panel data from 1870 to 2016. They consider two measures of inequality, the Gini coefficient and the income share of the richest 10% of the population. They estimate them using the vector autoregression method. The results show that income inequality initially reacts negatively to positive innovation shocks, but that this effect becomes positive with a certain time lag for top income inequality. Moreover, education

significantly reduces top income inequality. In the context of Islamic countries, Shahabadi et al. (2017) analyze the effect of variables such as education, innovation (number of scientific papers), information and communication technology (ICT), and income inequality measured by the Gini index. By estimating a panel data model, the results show that innovation has a positive but insignificant effect on income inequality, education has a negative and significant effect on inequality, and ICT has a negative and insignificant effect on income inequality in Islamic countries.

The studies presented above remain important contributions. They show positive, negative, and neutral results on the impact of innovation on income inequality. However, they point to three limitations that justify the contribution of this article. The first limitation is that most of the work on the impact of innovation on income inequality has been done in developed countries. However, Africa presents an interesting field of empirical investigation with respect to issues related to income inequality. Second, to our knowledge, there are no studies that have examined the direct and indirect effects of innovation on income inequality. Third, very few studies address the non-linear relationship between innovation and income inequality. This paper therefore proposes to address these limitations through an empirical analysis.

3. Data and methodology

3.1. Data

Our sample covers 48 African countries and the data come from various sources: World Development Indicators (WDI), World Intellectual Property Organization (WIPO), United Nations Conference on Trade and Development (UNCTAD), international Monetary Fund (IMF), International Labour Organization (ILO), Standardized World Income Inequality Database (SWIID). The periodicity of the study is chosen according to data availability constraints. The list of countries, the definition and the sources of all variables used in this study are presented in the annex (Tables A1 and A2).

3.1.1. Dependent variables

The debate on measures of income inequality remains open in the literature (Jonathan and Khandker, 2009), but the most popular measure is the Gini coefficient, which is derived from the Lorenz curve. It oscillates between 0 and 1, with 0 indicating perfect equality and 1 perfect inequality (Gu and Wang, 2021). This paper does not favor one measure of income inequality over the other, but instead uses multiple measures, not only motivated by the recent literature (Aghion et al., 2019 ; Asongu and Odhiambo, 2020), but also to ensure the consistency of our results¹. The first measure is the Gini coefficient from the WDI (2022), the second measure is the Palma ratio (Pre-tax national income). Data on the share of pre-tax income held by the top 10 percent of earners in our

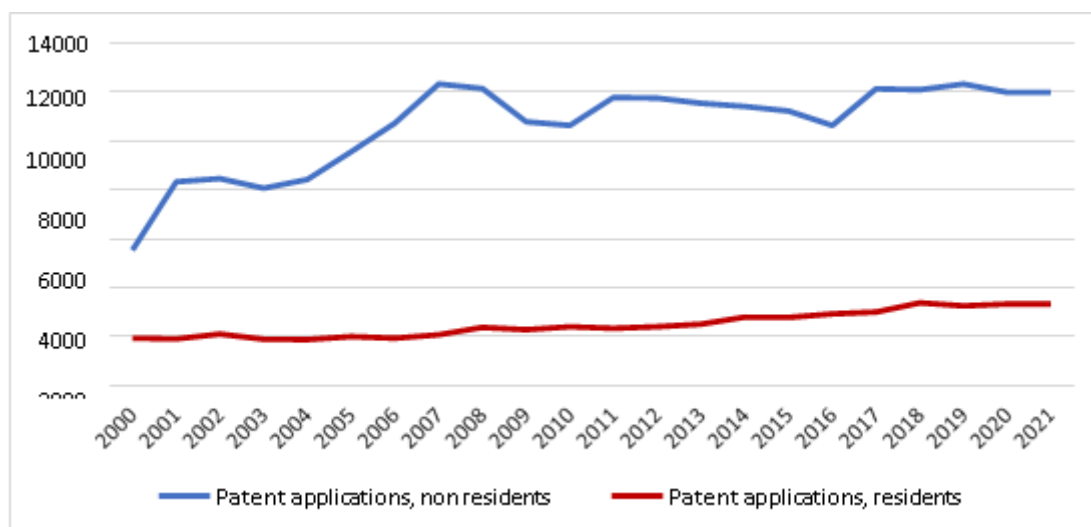
country panel analysis are taken from the World Wealth and Income Database (Alvaredo et al., 2017). The third measure is net personal wealth, also taken from the previous database. It represents the net personal wealth of the top 10%. Finally, the standardized world income inequality database (Frederick Solt, 2016) was chosen for the Gini index. It is the estimate of the Gini index of inequality in equivalized (square root scale) household disposable income (post-tax, post-transfer).

3.1.2. Variable of interest

In this paper we will use as the main measure of innovation the number of patents (resident and non-resident) from WIPO. Thus, in the analysis it is brought back per capita. This measure is mainly based on the work of Law et al. (2020).

The number of patents is a crude measure of innovation, as a patent with a large contribution to the literature and a patent with a small contribution receive the same weight (Aghion et al, 2018). As can be seen in Figure 2, the number of patents in Africa is evolving over the period 2000 to 2021, with the evolution being more pronounced for non-resident than resident patents. Without claiming to be exhaustive, this could be the result of African governments' efforts to invest in research, which helps to stimulate innovation (World Bank, 2018). In addition, as White (2005) points out, the spread of intellectual property laws has encouraged firms to invest in research and patenting. Another argument is that international collaboration between African and foreign firms has stimulated innovation and increased the number of patents filed (UNCTAD, 2012).

Figure 2: Innovation Trends in Africa



Source: authors, data retrieved from WIPO

3.1.3. Control variables

To test the hypothesis postulating a relationship between innovation and income inequality, we also include a number of controls that are likely to be correlated with the two key variables. For the baseline model regressions, we control for access to electricity, trade openness, CO2 emissions, government consumption expenditures, and total natural resource rents. The control variables selected in this work are motivated by a large literature (Aghion et al., 2019; Law et al., 2020; Hailemariam et al., 2021). The more detailed descriptive information of the dependent variables, independent variables, and other control variables are respectively summarized in Table A2 in the Appendix. Table 1 presents the results of Pesaran's (2004) cross-sectional dependence tests. For our sample of 48 African countries, the independent null hypothesis of Pesaran (2004) is rejected at the 1% significance levels, indicating that the cross-sections are interdependent.

Table 1 : CD-test for cross-sectional dependence

Pesaran (2004)		
Variable	Test statistics	p-value
Gini index	1.228	0.219
gini_disp	-2.537	0.011
Palma ratio	2.421	0.015
wealth	2.211	0.027
Innovation	2.433	0.015
Electricity	131.73	0.000
Trade	15.928	0.000
CO2	110.292	0.000
Gov_consum	5.363	0.000
Resources rents	39.036	0.000

Notes: Under the null hypothesis of cross-section independence, $CD \sim N(0,1)$.

Source: authors

Table 2: Descriptive statistics and correlation

Variable	Gini_index	gini_disp	Palma	wealth	Innov	Elect	Trade	CO2	Gov cons	RN
Obs.	1059	1135	1017	1040	1166	1098	1021	1060	981	1074
Mean	4.433	3.785	0.601	0.617	247.59	42.518	68.874	8.038	15.088	12.217
Std. Dev.	0.116	0.161	0.067	0.098	1000.66	28.761	35.107	1.855	7.143	12.213
Min	3.813	3.464	0.46	.394	0	0.643	0.757	3.912	0.952	0.001
Max	4.93	4.176	0.777	.809	8317	100	347.997	13.012	56.854	67.89
Matrix of correlations										
(1) Gini	1.000									
(2) gini_disp	0.698	1.000								
(3) Palma	0.801	0.795	1.000							

Variable	Gini_index	gini_disp	Palma	wealth	Innov	Elect	Trade	CO2	Gov_cons	RN
(4) wealth	0.433	0.419	0.551	1.000						
(5) Innov.	0.201	0.284	0.111	-0.084	1.000					
(6) Elect.	-0.184	-0.111	-0.268	-0.259	0.376	1.000				
(7) Trade	0.155	0.105	0.186	0.026	-0.099	0.236	1.000			
(8) CO2	-0.165	-0.022	-0.238	-0.186	0.578	0.680	-0.090	1.000		
(9) Gov_c	0.255	0.309	0.335	0.095	0.046	0.074	0.423	-0.070	1.000	
(10) RN	-0.133	-0.184	-0.133	0.065	-0.091	-0.082	0.100	0.041	-0.157	1.000

Source: authors

A summary reading of Table 2 shows that innovation is positively correlated with the various income inequality variables. This means that the production of innovation in Africa is associated with the increase in income inequality. There are several possible explanations. On the one hand, the enormous costs associated with research and development limit access for low-income individuals. On the other hand, innovative firms, for example, have high skill requirements that exclude workers with low levels of skills and education. However, the result of this correlation could not confirm these hypotheses, so only an empirical analysis will give credibility to this result, hence the purpose of the underlying sections.

3.2. Methodology

In this study, we estimate the effect of innovation on income inequality for a panel of 48 countries observed over the period 2000-2021. We adopt a multiple regression model that establishes the relationship between inequality and innovation, inspired by Lee and Rodríguez- Pose (2013). The theoretical model is written as follows:

$$Inequality_{it} = \alpha_0 + \alpha_1 Innovation_{it} + \alpha_2 X_{it} + \varepsilon_{it} \quad (1)$$

Where $Inequality_{it}$ is the income inequality of a country i at period t , $Innovation_{it}$

The innovation variable and model is given by: X_{it} represents the vector of control variables. The exploded form of the model is given by:

$$Inequality_{it} = \alpha_0 + \alpha_1 Innovation_{it} + \alpha_2 Electricity_{it} + \alpha_3 Trade_{it} + \alpha_4 CO_{2it} + \alpha_5 GovCons_{it} + \alpha_6 Res\_rents_{it} + \varepsilon_{it} \quad (2)$$

Our panel data exhibit the problem of cross-sectional dependence according to the result in Table 1, so equation (2) is estimated using the estimation method of Driscoll and Kraay (1998) to solve this problem. However, Driscoll and Kraay's model assumes a static relationship between our variables, which may not be the case. Although Driscoll and Kraay's method is simple to implement, it does not account for unobserved heterogeneity and the possibility of

endogeneity. To address this problem, we use several methods to solve the endogeneity including the 2SLS instrumental variable method of Lewbel (2012), the Kiviet method (2020), as well as the System Generalized Method of Moments (S-GMM).

In contrast to the use of the ordinary instrumental variables technique, Lewbel's technique provides some robustness to our results. In fact, it is often difficult to find suitable instruments that simultaneously satisfy these conditions, which is a major problem for the use of instrumental variable estimators in most applied research (Baum et al., 2012; Stock et al., 2002). To overcome this problem, the study uses Lewbel's two-stage least squares (2SLS) technique, which is applied when identification sources, such as appropriate external instruments, are unavailable or weak. Lewbel's 2SLS approach is essential for identifying structural parameters in regression models with an endogenous or poorly measured regressor in the absence of traditional identification information. This method incorporates internal instruments based on heteroskedasticity. The internal instruments are generated from the residuals of the auxiliary equation, which are multiplied by each of the included exogenous variables in mean-centered form. An advantage of Lewbel's 2SLS approach is that it does not depend on the satisfaction of standard exclusion restrictions.

4. Results

4.1. Baseline results

Table 3 presents the results of the estimation of the effect of innovation on income inequality in Africa obtained from the estimation by the Pooled Ordinary Least Squares (POLS) method. The first row of the table presents the estimation technique, the second presents the dependent variable. On the other hand, the first column presents the list of independent variables of the analysis. The results show that innovation increases income inequality in Africa, regardless of the measure of inequality used. Specifically, the increase in innovation is on average associated respectively with an increase in the Gini index of 0.16%, in disposable income inequality of 0.25%, in the palma inequality index of 0.07%, and in the wealth distribution index of 0.02% at a significance level of 1%. Three explanations are advanced to support this result. First, innovation directly creates income inequalities by generating an imbalance in the structure and organization of labor and wage markets. Second, technological change favors the most skilled workers and thus may accelerate the replacement of the unskilled workforce. Third, innovation causes income dispersion among entrepreneurs. This result is similar to the one found by Aghion et al. (2019) who when examining the overall effect of innovation on income inequality find a positive effect.

Table 3: Innovation and Inequality, Driscoll-Kraay

	Method: Pooled OLS			
	<u>Gini index</u>	<u>gini_disp</u>	<u>Palma</u>	<u>wealth</u>
	(1)	(2)	(3)	(4)
<u>Innov</u>	0.0016*** (0.0001)	0.0025*** (0.0001)	0.0007*** (0.0001)	0.0002** (0.0001)
Electricity	-0.0012*** (0.0002)	-0.0009*** (0.0003)	-0.0010*** (0.0001)	-0.0010*** (0.0001)
Trade	0.0006*** (0.0001)	0.0006* (0.0003)	0.0005*** (0.0002)	0.0002*** (0.0001)
CO ₂	-0.0088* (0.0044)	-0.0167*** (0.0037)	-0.0017 (0.0023)	-0.0000 (0.0026)
<u>Gov_consum</u>	0.0020* (0.0010)	0.0023*** (0.0004)	0.0010 (0.0006)	0.0009 (0.0005)
<u>resourcesrents</u>	-0.0018*** (0.0005)	-0.0031*** (0.0004)	-0.0008*** (0.0003)	0.0006*** (0.0002)
Constant	4.497*** (0.0457)	3.913*** (0.0345)	0.607*** (0.0154)	0.633*** (0.0242)
Observations	832	876	799	801
R-squared	0.2145	0.2460	0.2350	0.0816
Countries	45	48	45	45

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Source: authors

Access to electricity reduces income inequality in Africa. A one-unit increase in electricity access coverage reduces income inequality as measured by the Gini index by 0.12%, disposable income inequality by 0.09%, the Palma inequality index by 0.1%, and the wealth distribution index by 0.1% at the 1% significance level. This result shows that, overall, the reduction of income inequality in Africa must be achieved through universal access to electricity. This result is in line with what Topcu and Tugcu (2020) find when they examine the negative impact of renewable energy on income inequality. Second, trade in goods and services has a positive and significant impact on income inequality in Africa. The distribution of income in Africa supports the hypothesis that the technology gap and the skill-dependent nature of new technologies may be important factors in shaping the distributional effects of trade. This result is consistent with Meschi and Vivarelli (2009), who find that trade increases income inequality in developing countries. Third, a unit increase in CO₂ emissions is associated with a 0.88% decrease in income inequality and a 1.67% decrease in disposable income inequality at the 10% and 1% significance levels, respectively. This result suggests that an increase in CO₂ emissions is associated with a reduction in income inequality in Africa. This result is consistent with the analysis of Ravallion et al. (2000) who argue that higher inequality is associated with lower levels of CO₂ emissions. For government consumption, the increase is associated on average with the increase in income inequality of 0.2% and 0.23% at thresholds of 10% and 1% respectively. This result shows that government consumption accelerates the increase in income

inequality through an increase in the tax base to offset the additional increase (Anderson et al., 2017). Finally, increasing resource rents by one unit leads to a decrease in income inequality by 0.18%, in the distribution of disposable income by 0.31%, and in the palma index by 0.08% at a 1% significance level; whereas, increasing resource rents exacerbates income inequality based on distributed wealth at a 1% level. The first result is similar to that found by Kim and Lin (2018) who in their study analyze the effects of oil abundance on income inequality. The second result is justified by the work of Tadadjeu et al. (2021) who find that natural resources increase wealth inequality.

4.2. Endogeneity issue

In this section, we argue that the positive correlation between innovation and income inequality reflects, at least in part, an endogeneity problem. The endogeneity problem could arise from three sources. The first is reverse causality between income inequality and innovation. Reverse causality is likely because people in a country with low inequality (due to transfers, i.e., government payments to individuals through social programs such as welfare, scholarships, and even social security) may have little incentive to innovate (Law et al., 2020); conversely, an increase in income may allow incumbent firms to erect barriers to new entrants, thereby reducing and inducing innovation. Second, measurement error. The variables we use to measure innovation or income inequality may be subject to measurement error, especially for African countries. Third, omission of variables. Indeed, it is clear that our basic model does not control for all possible determinants of income inequality. Unfortunately, some of them are very regularly omitted from the endogeneity treatment, which could bias the results. To deal with this problem, as indicated in the previous sections, we will use Lewbel's 2SLS method and Kiviet (2020).

- Cut-off values and omitted variable bias.

Although the results in Table 4 are interesting because they control for the temporal determinants of income inequality, they are far from sufficient as determinants of income inequality. Identifying the causal effect of innovation and income inequality is far from trivial. In particular, the POLS estimator is not consistent if there are omitted time factors that are related to income inequality and affect innovation. To address the problem of omitted variable bias, and following Domguia et al. (2022) the limit analysis of Oster (2019) was adopted.

Generally, the literature assumes that the inclusion of control variables stabilizes the coefficients and reduces omitted variable bias. However, Oster (2019) cautions against relying solely on coefficient stability, as stable coefficients may result from the addition of uninformative control variables. Oster's approach advocates considering the R² value along with coefficient stability, thereby limiting omitted variable bias and partial identification of

causality. A comparison between "uncontrolled" and "controlled" regressions under certain selection assumptions achieves this goal. To ensure accurate results, this study analyzed different indicators of income inequality separately. Figure 2 report the bounds on the β values of the model via POLS with full controls. We see that the bounds identified for each of our four income inequality variables include zero, suggesting that our estimates are not biased by omitted variables.

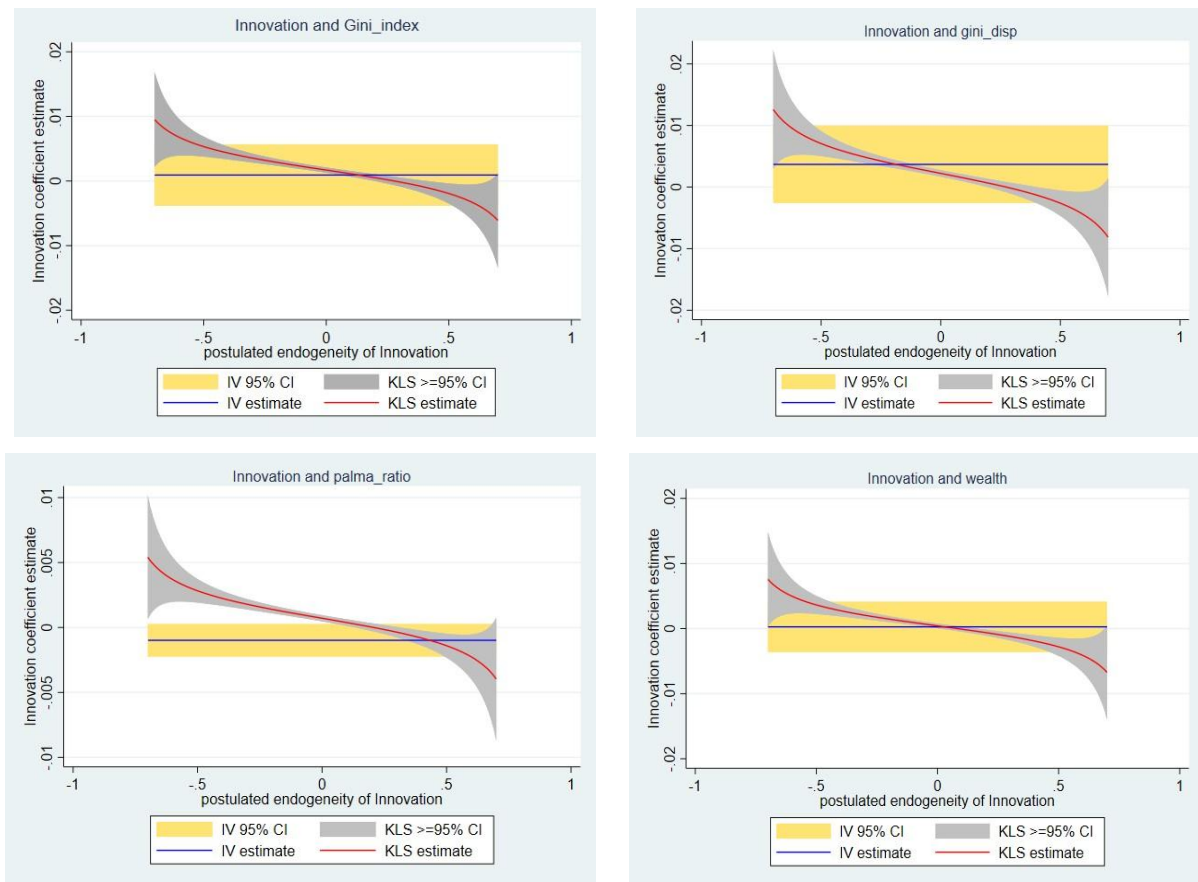
Table 4: Kiviet (2020) estimate

	Method: <u>Kiviet (2020)</u>			
	<u>Giniindex</u>	<u>gini_disp</u>	Palma	wealth
	(1)	(2)	(3)	(4)
<u>Innov</u>	0.0029*** (0.0003)	0.0038*** (0.0004)	0.0014*** (0.0002)	0.0015*** (0.0002)
Electricity	-0.0012*** (0.0002)	-0.0005* (0.0003)	-0.0009*** (0.0001)	-0.0007*** (0.0002)
Trade	0.0006*** (0.0002)	0.0003 (0.0002)	0.0005*** (0.0001)	0.0002 (0.0001)
CO2	-0.0213*** (0.0039)	-0.0323*** (0.0052)	-0.0083*** (0.0028)	-0.0176*** (0.0042)
<u>Gov_consum</u>	0.0008 (0.0009)	0.0037*** (0.0011)	0.0012** (0.0005)	-0.0008 (0.0008)
<u>resourcesrents</u>	-0.0021*** (0.0005)	-0.0016*** (0.0006)	-0.0008*** (0.0003)	0.0008* (0.0004)
Constant	4.6070*** (0.0340)	4.0066*** (0.0446)	0.6511*** (0.0234)	0.7845*** (0.0356)
Observations	501	513	478	478
rank	7	7	7	7
<u>xkurtosis</u>	32.58	33.38	31.17	31.17
<u>grid_min</u>	-0.700	-0.700	-0.700	-0.700
<u>grid_max</u>	0.700	0.700	0.700	0.700
<u>grid_step</u>	0.0100	0.0100	0.0100	0.0100
<u>corr</u>	-0.200	-0.200	-0.200	-0.200

Note: Robust standard errors are in parentheses. ***, **, *: represent the significance thresholds at 1%, 5% and 10% respectively.

Source: authors

Figure 2 : Cut-off values and omitted variable bias.



Source: authors

- Endogeneity Correction with Lewbel 2SLS

POLS estimation shows a positive and significant relationship between innovation and all innovation variables. However, the results may be biased and inconsistent due to the presence of endogeneity (reverse causality, omitted variables, and measurement errors). Therefore, to ensure that the results are robust to endogeneity, Lewbel's (2012) approach is used as robustness estimation techniques. The results compiled in Table 5 firstly show that all equations (1) - (4) are favorable to Hansen and endogeneity diagnostic tests, which shows that indeed the endogeneity problem is addressed in our new estimates. Thus, the result obtained shows that innovation is positively and significantly associated with 1% of income inequality in Africa. This result corroborates the findings of Law et al (2020) in their analysis using an instrumental variable method. The finding is the same for our control variables which retain their signs.

Table 5: Innovation and Inequality (Lewbel 2SLS)

	Method: Lewbel 2SLS			
	<u>Gini index</u>	<u>gini_disp</u>	<u>Palma</u>	<u>wealth</u>
	(1)	(2)	(3)	(4)
<u>Innov</u>	0.0016*** (0.0001)	0.0025*** (0.0001)	0.0007*** (0.0001)	0.0002** (0.0001)
Electricity	-0.0012*** (0.0002)	-0.0009*** (0.0003)	-0.0010*** (0.0001)	-0.0010*** (0.0001)
Trade	0.0006*** (0.0001)	0.0006* (0.0003)	0.0005*** (0.0002)	0.0002*** (0.0001)
CO2	-0.0088* (0.0044)	-0.0167*** (0.0037)	-0.0017 (0.0023)	0.0000 (0.0026)
<u>Gov_consum</u>	0.0020* (0.0010)	0.0023*** (0.0004)	0.0010 (0.0006)	0.0009 (0.0005)
Resources rents	-0.0018*** (0.0005)	-0.0031*** (0.0004)	-0.0008*** (0.0003)	0.0006*** (0.0002)
Constant	4.497*** (0.0457)	3.913*** (0.0345)	0.607*** (0.0154)	0.633*** (0.0242)
Observations	501	513	478	478
R2	0.218	0.202	0.242	0.804
F-Statistics	24.30***	22.23***	27.11***	6.701***
Hansen J. stat (p-value)	0.461	0.380	0.230	0.771
<u>Endogeneity Test (p-value)</u>	0.0064	0.0295	0.0004	0.0062

Note: Robust standard errors are in parentheses. ***, **, *: represent the significance thresholds at 1%, 5% and 10% respectively. Hansen J Statistic: H0: over-identification restrictions are valid. Endogeneity Test: H0: specified endogenous variables can be treated as exogenous .

Source: authors

4.3. Robustness check

4.3.1. Robustness through S-GMM.

Since income inequality is a dynamic process that exerts a strong inertia on these past values, it becomes important to take this inertia into account. We introduce the lagged variable of income inequality in equation (2) for the next step of our analysis. This step is given by equation

(3) below:

$$Inequality_{it} = \alpha_0 + \alpha_1 Inequality_{it-1} + \alpha_2 Innovation_{it} + \alpha_3 X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (3)$$

The introduction of the lagged variable $Inequality_{it-1}$ of income inequality leads to a dynamic model in which μ_i is the unobserved country-specific effect, v_t is a time-specific effect. The other expressions reflect the same elements described in the previous equations. The advantage of dynamic models over static models is that they take into account more information about the dynamics of

our dependent variable, but there is a high risk of high correlation between the error term and the lagged dependent variable, usually known as Nickell bias (1981).

Referring to the work of Law et al. (2020) and Ongo-Nkoa et al. (2023), we use GMMs because this method has the advantage of taking into account heteroskedasticity and cointegration in panel data, measurement errors, variable omissions, endogeneity problems, but also unobserved country-specific effects. This method makes it possible to control for individual and time-specific effects and to overcome endogeneity biases of the variables, in particular when there are one or more lags of the dependent variable listed as an explanatory variable. The choice of GMM-system is more appropriate than differential GMM. It is more robust to heteroskedasticity and autocorrelation (Miao et al., 2017). As GMM is otherwise an instrumental variable method, it consists of estimating the equations using the lagged values of the explanatory variables as instruments as proposed by Arellano and Bond (1991).

The results are presented in Table 6. Overall, the results of the diagnostic tests show that our models are well specified. The Hansen test does not reject the validity of the instruments and the lack of second-order serial correlation is not rejected. A large number of instruments may bias the Hansen test due to excessive identification restrictions and therefore the rule of thumb is that the number of instruments should be less than the number of countries (Roodman, 2009). The GMM estimation results for the system generated a maximum of 35 instruments, which is less than the number of countries, and thus the results are valid.

The lagged dependent variable at (t-1) in each of the estimates is positive and significant, confirming the dynamic nature of income inequality. Access to electricity, trade openness, CO2 emissions and natural resource rents explain the dynamics of income inequality for the countries in the sample. Their sign remains invariant to our previous estimates. As regards the coefficients associated with innovation, they are respectively the income inequalities at 1% in all the estimates (columns 1-4). The result obtained here is also in line with those of Law et al (2020) who, using a dynamic method in robustness, verify that innovation increases income inequality.

Table 6: Evidence from S-GMM estimate

	<i>System-GMM</i>			
	<u>Gini_index</u>	<u>gini_disp</u>	<u>Palma</u>	<u>wealth</u>
	(1)	(2)	(3)	(4)
<u>Innov</u>	0.002*** (0.000)	0.003*** (0.000)	0.001*** (0.000)	0.001*** (0.000)
Electricity	0.001*** (0.000)	0.001*** (0.000)	-0.000*** (0.000)	-0.000* (0.000)
Trade	0.000*** (0.000)	0.000*** (0.000)		0.000** (0.000)
CO2	-0.023*** (0.005)	-0.034*** (0.003)		-0.002 (0.002)
<u>Gov_consum</u>	0.002** (0.001)	0.003*** (0.000)		0.001*** (0.000)
<u>resourcesrents</u>	-0.000 (0.000)	-0.000*** (0.000)		-0.000* (0.000)
<u>Lag.Giniindex</u>	0.088*** (0.031)			
<u>Lag.gini_disp</u>		0.014*** (0.001)		
<u>Lag.Palma</u>				0.930*** (0.006)
<u>Lag.wealth</u>				
Constant	3.899*** (0.033)	3.951*** (0.018)		0.585*** (0.023)
Observations	474	513	478	478
Countries	45	45	43	43
Instruments	32	35	32	32
AR (1)	0.0377	0.0034	0.0002	0.0010
AR (2)	0.938	0.600	0.448	0.193
Hansen OIR	0.564	0.590	0.361	0.267

Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: authors

4.4. Is there a non-linear effect?

In this analysis, we check that the relationship between innovation and income inequality is not linear. Thus, to achieve this, we proceed by squaring the innovation variable in Table 7.

The empirical results obtained using a dynamic panel GMM model reveal a non-linear inverted U-shaped relationship between innovation and income inequality, which implies a reduction in the income inequality gap at the end of the innovation phase in countries. However, this improvement is only dynamically sustainable after a certain threshold. Any level of innovation before this threshold has an opposite effect, worsening income inequality.

Table 7: Non-linear effect analysis.

	System-GMM			
	<u>Gini index</u>	<u>gini_disp</u>	Palma	wealth
	(1)	(2)	(3)	(4)
Innovation	0.000879*** (0.000270)	0.000841*** (0.000681)	0.00116*** (0.000199)	0.000110*** (0.000550)
Innovation*Innovation	-0.000074*** (0.000278)	-0.000319*** (0.000569)	-0.0000434** (0.000189)	-3.59e-09*** (0.0000516)
Electricity	-0.00117*** (0.000274)	0.00117*** (0.000104)	-0.0129*** (0.00196)	-0.000333*** (0.0000438)
Trade	0.000264*** (0.000627)	0.000422*** (1.83e-05)	0.00976*** (0.00283)	-0.000178*** (0.0000611)
CO2	-0.0212*** (0.00448)	-0.0411*** (0.00284)	-0.449*** (0.0813)	-0.0304*** (0.000591)
<u>Gov_consum</u>	0.00184* (0.000943)	0.00313*** (0.000384)	-0.0181* (0.00973)	0.00219*** (0.000107)
<u>resourcesrents</u>	-0.000503** (0.000253)	-0.000148*** (4.94e-05)	-0.0581*** (0.00415)	0.000898*** (1.51e-05)
Constant	4.594*** (0.0438)	3.995*** (0.0212)	4.337*** (0.725)	0.857*** (0.00428)
Observations	463	513	478	478
Countries	44	45	43	43
Instruments	32	35	28	27
AR (1)	0.0458	0.571	0.373	0.00125
AR (2)	0.303	0.579	0.361	0.415
Hansen OIR	0.226	0.616	0.52	0.503

Source: authors

4.5. Analyzing the mediating effect

In this analysis, we explore different mediators through which innovation could influence income inequality. With reference to the existing literature, three main mediators are selected: globalization, the quality of governance and remittances. Law et al (2020), consider individual variables, such as innovation, and the interaction between two individual variables (globalization and financial development) as a primary concern.

Our empirical approach involves the subsequent estimation of two regression equations, as described below:

$$\text{Model 1: } Med_{it} = \alpha_1 + b_1 \text{Innovation}_{it} + c'_1 X_{it} + \mu_i \quad (4)$$

$$\text{Model 2: } Inequality_{it} = \alpha_2 + b_2 \text{Innovation}_{it} + b_3 Med_{it} + c'_2 X_{it} + v_i \quad (5)$$

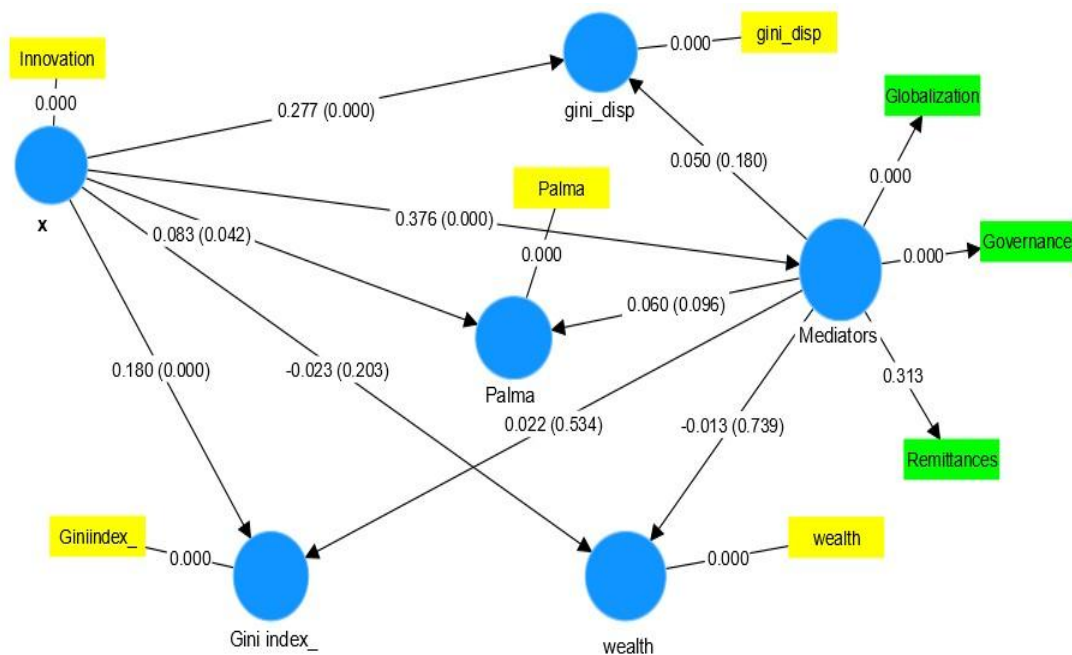
Where Med_{it} represents the mediating variables (globalization, governance quality, and remittances) The composition effect is derived from the above models as follows: Indirect pathways: $b_1 \times b_3$; Direct pathways: b_2 and Total pathways: $(b_1 \times b_3) + b_2$.

The direct paths (b_2) between innovation and the different indicators used to capture income inequality are significant, it is then possible to include the mediating variables in the model and to assess the significance of the indirect paths ($b_1 \times b_3$). The analysis reveals that our three channels effectively mediate the effects of innovation on income inequality. The contribution of the channels to the total effect of innovation on income inequality is calculated through the accounted variation. Following Hair et al. (2014) we use the Variance Account For (VAF) to assess the degree of mediation. It is derived from the calculation below:

$$VAF = \frac{\text{Indirect path}}{\text{Total path}} \\ = \frac{(b_1 \times b_3)}{[(b_1 \times b_3) + b_2]}$$

The results show that the total effect of innovation on income inequality indicators in Africa is mediated by globalization, governance and remittances at thresholds of 6.3%, 4.3%, 17.5% and 21% for the Gini index, Gini disp, Palma ratio and wealth inequality respectively. This finding is consistent with Stiglitz (2012), who finds that innovation and globalization are driving income inequality.

Figure 4: Mediation analysis



Source: authors

Conclusion

Rising income inequality threatens social cohesion, hinders economic development, and can cause recessions (Brzezinski, 2018). Thus, income inequality is emerging as a global problem that requires global and innovative solutions. The main objective of this study was to empirically examine the effect of innovation on income inequality in 48 African countries over the period 2000-2021. Two major facts have allowed us to address our problem: on the one hand, the widening gap between the levels of income on the African continent, due to many factors; and on the other hand, the relative evolution of the level of innovation on the continent. These two facts are concerns that are part of the global development agenda, including the United Nations Agenda 2023 for the achievement of Sustainable Development Goals (SDGs)². This renewed interest led us to assess the impact of innovation on income inequality in Africa. The analysis was possible using several estimation methods, including Driscoll and Kraay's pooled OLS, Kiviet (2020), Lewbel 2SLS and GMMs, to solve some specific econometric problems. This paper leads to several emerging results: first, innovation is positively and significantly associated with income inequality at a 1% threshold. Second, access to electricity, trade openness, CO₂ emissions and natural resource rents significantly reduce income inequality while the effect is opposite with government consumption expenditures. Third, the results reveal the non-linear inverted U-shaped relationship between innovation and income inequality. There is thus a threshold beyond which innovation becomes a factor in reducing income inequality in Africa. Fourth, the results reveal that the total effect of innovation on the indicators of income inequality in Africa is mediated by mediators (i.e. globalization, governance and remittances) at thresholds of 6.3%, 4.3%, 17.5% and 21% for the Gini index, Gini disp, Palma ratio and wealth inequality respectively. Ultimately, it is incumbent upon African countries to consider innovation not only as a decisive factor in the economic emergence of nations, but also as a potential vector that can widen the income gap between individuals. Without being exhaustive, some recommendations are made:

- (i) It would be essential to put in place policies for the appropriation and absorption of innovation in Africa.
- (ii) The results recommend diversifying the training of young people to give them the basis for creativity, which would enable them to have a substantial income.
- (iii) It is also recommended that heterogeneity be reduced in order to linearize income across populations.
- (iv) There is a need to share the nation's wealth and provide opportunities for innovation to all capabilities. Because all technical developments

have the potential to boost economic growth and productivity in the long run, innovation should be supported in all economies.

This paper, despite its ambitions, has two main limitations that should be taken into account for possible future research. First, a shortcoming would be the failure to use other measures of innovation to further contrast the results, and second, an extension in this direction could be the analysis of the non-linearity effect of the relationship between innovation and income inequality using new methods such as Panel Smooth Transition Regression (PSTR) to better detect regime shifts.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Funding

No financial support was received.

Appendixes

Table A1: List of countries in the sample

Angola	Mauritania	Nigeria
Benin	Mauritius	Rwanda
Botswana	Morocco	Senegal
Burkina Faso	Ethiopia	Sierra Leone
Burundi	Gabon	Somalia
Cabo Verde	Gambia	South Africa
Cameroon	Ghana	Sudan
Central African Republic	Guinea	Tanzania
Chad	Guinea-Bissau	Togo
Comoros	Kenya	Tunisia
Congo, Dem.	Lesotho	Uganda
Congo, Rep.	Libya	Zambia
Cote d'Ivoire	Madagascar	Zimbabwe
Djibouti	Mali	
Egypt	Mozambique	
Equatorial Guinea	Namibia	
Eswatini	Niger	
<i>Source: authors</i>		

Table A2: Variable description and source

Variables	Abbreviation	Description	Source
Gini index	Gini index	Represents the Gini index of the income distribution	WDI (2022)
Pre-tax national income	Palma ratio	Pre-tax national income is the sum of all pre-tax personal income flows accruing to the owners of the production factors, labor and capital, before taking into account the operation of the tax/ transfer system, but after taking into account the operation of pension system.	WID (2022)
Net personal wealth	Wealth_	Net personal wealth Top 10%	WID (2022)
Total natural resources rents	resources rents	Total natural resources rents are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents (% of GDP)	WDI (2022)
Gini index	gini_disp	Estimate of Gini index of inequality in equivalized (square root scale) household disposable (post-tax, post-transfer) income, using Luxembourg Income Study data as the standard.	SWIID (2021)
Access to electricity	Electricity	Access to electricity is the percentage of population with access to electricity. (% of population)	WDI (2022)
Trade openness	Trade	Sum of exports of goods and services (% of GDP)	WDI (2022)
CO2 emissions	CO2	Stemming from the burning of fossil fuels and the manufacture of cement.	WDI (2022)
Financial Development	FD	Domestic credit to private sector refers to financial resources provided to the private sector by financial corporations, such as through loans, purchases of no equity securities, and trade credits and other accounts receivable, that establish a claim for repayment (% GDP)	WDI (2022)
Remittances received	Remittances	Personal remittances comprise personal transfers and compensation of employees. (% of GDP)	WDI (2022)

Source: authors

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Notes

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- ¹ Indeed, the Gini index alone, for example, is not entirely satisfactory (the Gini coefficient may decrease while the number of poor people increases) (see related discussions in Sitthiyot and Holasut, 2020). Therefore, for the country-level analysis, we introduce two additional measures of income inequality to ensure that the results are robust.
- ² Specifically, this is reflected in SDG 10.1 "Reduce income inequality" and SDG 9 "Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation".

Emerging technologies in South Africa: A sectorial innovation systems analysis

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Abstract

Technologies have become increasingly pervasive across society. However, technologies change over time as improvements or radical new ways of doing things are found. This creates a space for what some term 'emerging technologies'; a set of technologies that are novel, gain momentum and have the potential to influence economic growth and impact positively or negatively on development goals. Emerging technologies are characterised by radical novelty, relatively fast growth, coherence, prominent impact, uncertainty and ambiguity. This paper outlines the findings of a landscaping assessment of emerging technologies in South Africa. By providing details on the barriers and opportunities for emerging technology, the study adds a level of empirical data to the field which will be of benefit to South African policy makers and other stakeholders. For example, the empirical results of the analysis highlight the need to not define emerging technologies only with digital or the latest technologies. The characteristic of radical novelty in a developing economy context must leave room for other forms of technology that are radical and new to an environment (not necessarily just new to the world). The other major empirical result relates to the lack of dedicated policies and strategies to support technological emergence in South Africa. However, the study also enabled members of the study team to interrogate the notion of systems of innovation and their boundaries. This, given the increasing interest in the degree to which some 4IR technologies (notably artificial intelligence technologies) can be seen as potential or actual 'general purpose technology'. The paper finishes with reflections on the implications of this for the sectoral innovation systems approach.

Keywords: Emerging Technology, Novelty, Innovation, General Purpose Technologies, Sectoral Innovation Systems, South Africa.

1. Introduction

Technologies are increasingly pervasive across society. We use them to communicate, to prepare our food, in manufacturing, teaching, and healthcare, etc. Technologies change over time as improvements or radical new ways of doing things are found. This creates a space for what some term ‘emerging technologies’; a set of technologies that are novel, gain momentum having the potential to create new economic sectors and impact positively or negatively on development goals.

The Fourth Industrial Revolution (4IR) in the form of new and emerging technologies is expected to transform the economy, encouraging economic growth and structural transformation for Africa (Ndung’u and Signé, 2020). In South Africa, the adoption of 4IR-related technologies is far from widespread but is currently concentrated in a few large firms and a few advanced manufacturing activities; this is not unique to South Africa but a worldwide phenomenon (UNIDO, 2019). The opportunities and impacts on employment and skills are also heterogeneous as they differ vastly across technologies and sectors, and occupations. The concentration in the adoption of such technologies in a few firms and sectors, as well as the potential polarisation of the labour market, raise concerns in terms of the negative impacts that the adoption of 4IR technologies may have on the national distribution of income and wealth (Kraemer-Mbula and Mazibuko-Makena, 2020). These new technologies, sometimes referred to as ‘disruptive technology’, will create new markets and business practices, different requirements for the labour market and ultimately impact the income of workers (Leipziger and Dodev, 2016). In some cases, these new technologies change the pace of business, as firms feel they must adapt quickly or lose out (Fredberg & Pregmark, 2022). Understanding these dynamics is particularly important in a country like South Africa, which cannot afford higher inequalities and job losses, having one of the highest inequality levels in the world.

There are several initiatives driven by different government departments and stakeholders supporting the unfolding of the 4IR in SA. One of the most notable has been the establishment of the Presidential Commission on the Fourth Industrial Revolution (4IR) in 2019. The 30-member Commission put together experts across different sectors of society to assist the government in taking advantage of the opportunities presented by the digital industrial revolution. Chaired by the country’s President, the Commission identified a set of priorities, strategies, and action plans to position South Africa as a competitive global player in 4IR. Another is the South Africa 4IR Centre hosted at the Council for Scientific and Industrial Research (CSIR). This has an official partnership with the World Economic Forum and is part of a network of similar centres around the world. It has a governmental remit to promote and develop governance and policy frameworks to enable South African businesses

and government departments better take up, utilise, and regulate these emerging technologies.

Recognising the increasing importance emerging technologies will have, a landscaping and assessment of existing and future potential emerging technologies was conducted by the authors and a broader team in 2022¹. This research was commissioned by the Foreign Commonwealth and Development Office, through its Eastern and Southern Africa Research and Innovation Hubs and the Science and Innovation Network teams, as part of their efforts to support the strengthening of research and innovation ecosystems in Africa.

This paper outlines the findings of the landscape analysis which used the components from a sectoral innovation systems approach to examine the innovation landscape situation. By providing details on the barriers and opportunities for emerging technology, the study adds a level of empirical data to the field which will be of benefit to South African policy makers and others. However, the study also enabled members of the study team to interrogate the notion of systems of innovation and their boundaries given the increasing interest in the degree to which some 4IR technologies that are emerging in South Africa – notably artificial intelligence technologies – can be seen as potential or actual ‘general purpose technologies’ (Agrawal et al, 2023; Bresnahan, 2019; Cockburn et al, 2018; Trajtenberg, 2018)

The paper begins by introducing the literature on emerging technologies and sectoral innovation systems in Section 2. The methodology adopted is outlined in Section 3. Analysis and findings of the study are presented in Section 4 while the discussion and conclusion are presented in Sections 5 and 6 respectively.

2. Literature review

2.1 The literature defining emerging technology

Rotolo et al (2015) reviewed the academic literature to understand how the concept of ‘emerging technologies’ was being defined. They noted five core characteristics of these technologies which can be used to define them. The first characteristic is radical novelty. This does not necessarily always refer to a radical new technology being developed and commercialized. It also includes a new application of the technology in a new combination or area of attention. The second characteristic is relatively fast growth. This is characterised by the technology becoming popular i.e., it gains attention from investors and potential users more quickly than other similar technologies. The third characteristic is coherence relating to the instance when the technology becomes identifiable (from what came before it), and a set of actors coalesce around that technology. The fourth characteristic is prominent impact where the technology impacts an industry decisively by changing the balance or type of actors, institutions and knowledge. Lastly, uncertainty and ambiguity are

where the technology is still evolving and will only be fully understood (both in terms of process and outcome/ impact) in the future (Rotolo et al, 2015).

Such a definition does not lend itself well to a definitive list of technologies. In fact, Rotolo et al (2015) clearly articulate that context matters and therefore what is seen as an emerging technology in one context will not necessarily be seen as an emerging technology in another.

In the context of South Africa, the term emerging technologies competes with the concepts of 'frontier technology' (Mokoena, 2021) and the 'fourth industrial revolution' as per the Presidential Commission discussed above. The Department of Science and Innovation (DSI) 2020-2025 Strategic Plan does however have an outcome statement that features emerging technologies:

"Over the next five years, improve the sustainability and competitiveness of traditional sectors of the economy and initiate/continue research and development in emerging technology areas that could enable the creation of non-traditional South African economic sectors" (DSI, 2020: 47).

2.2 Innovation systems for analysing technology emergence

This study utilizes innovation studies thinking to understand the landscape for emerging technologies in South Africa. The emergence of new technologies is at the heart of innovation studies thinking. Schumpeter's early work, Nelson and Winter's in the 1970s and Freeman and Soete's work in the 1990s on technological change is linked to the idea of new or improved technologies being developed and commercialized (Cozzens et al, 2010). Innovation relates to the conceptualisation, design, development, piloting, roll out and uptake of a new product, process, business model or way of organising. For this reason, innovation is often considered to be a tangible 'thing' but is also a process of innovation activities (OECD/ Eurostat, 2018).

Innovation, when considered as a process, relies on people and organisations and most importantly how these two elements work together. This requires flows of knowledge and learning and longer-term competences to be built. These flows and the building of competences are dependent on the rules and values that underpin how people and organisations work together. These rules and values are often called institutions. These elements can be simplified into a three-part analytical framework of knowledge and technologies, actors and networks and institutions. This three-part framework is utilised by the 'sectoral innovation systems' approach (Malerba, 2005).

In the context of this study, a national innovation systems approach (Lundvall, 1992) would perhaps have made more sense because of the focus of the landscape for emerging technology innovation within the geographical boundary of the nation state of South Africa. Alternatively, the study could have utilised the technological innovation systems approach (Carlsson and

Stankiewicz, 1991) which over time has focused on seven functions that are needed for successful innovation of a specific technological product (see for example Hekkert et al, 2007).

We chose to take the sectoral innovation systems framework predominately because of its simplicity within the complexity of systems thinking. At the same time, while the sectoral innovation system has predominately been used in the context of analysing different industrial sectors (e.g. biotechnology (Cooke, 2002), ICT (Joseph, 2009), renewable energy (Hansen et al, 2018) and agriculture (Thitinunsomboon et al, 2008)), Malerba noted that sectors can be defined broadly or narrowly and that a key area in which sectoral innovation systems is useful is the emergence of new sectors and particularly the idea of clusters that span several sectors (Malerba, 2005). He writes that in these contexts transformation of a sector occurs through,

“the integration and fusion of previously separated knowledge and technologies as well as new relations and dynamics among different types of users and consumers, firms with different specialisation and competencies, and non-firm organisations and institutions (all of them grounded in previously separated sectors).”

The contention – as noted earlier – that some obvious emerging digital technologies such as those related to artificial intelligence can be seen as general-purpose technologies is an example of such new sector formations. This questions the validity of focusing analysis on industrial sector boundaries for example – a point we return to at the end of this paper.

The three elements of the sectoral innovation systems framework can be described as follows. With respect to knowledge and technology, Malerba (2005) asserts that a sector is shaped by the dominant technologies, knowledge and skills base and inputs available to the sector. The degree of innovation in technologies and the strength of the knowledge base, and the availability of inputs will determine whether and how the sector grows or contracts in size. The second part of the framework is made up of actors and networks. These are crucial in innovation systems thinking. Private firms are central to innovation systems but interact with a range of actors, including public sector organisations (e.g., universities, research centres, government departments) and the third sector (e.g., non-governmental organisations or community groups) as individuals (Malerba, 2005). In addition, sectoral innovation occurs across a range of geographical boundaries as many sectors rely on inputs from sources not always local to them, including product supply firms or investors in other parts of the country or abroad. The quantity and quality of interaction determines the intensity and type of innovation that takes place. This networking may be formal or informal, bilateral, and multi-lateral in nature and can involve the sharing of knowledge and skills and formal technology transfer or investment. The third element is institutions. These are the ‘rules of

the game' both formal (e.g., legislation and policy) and informal (e.g., attitudes and norms) as well as dominant narratives that determine how actors and networks operate and interact.

Underlying this approach (and other innovation systems approaches) is the complexity of the innovation process and the variety of combinations of knowledge/ technology, actors/ networks and institutions that are determined by the technology being innovated and/or the dynamics of one of the three elements. How these three elements connect and fit together are at the crux of innovation systems thinking. Being cognisant of these complex relationships between different structures (people and organisations) and institutions brings into focus the notion of agency (Giddens, 1976; Berger and Luckman, 1967) and the degree of power or capabilities that different actors have to influence their surroundings (Sen, 1999).

3. Methodology

In conducting this landscape analysis using the analytical framework of sectoral innovation systems, the study asked:

1. What is the current state of knowledge and technology in South Africa and what can be defined as emerging technologies using the five characteristics of Rotolo et al (2015)?
2. Who are the actors and how do they interact with the innovation system to support the emergence of these technologies in South Africa?
3. How are institutions supporting or obfuscating the emergence of technology in South Africa?

The study utilised a combination of desk review and interviews. Four separate desk reviews were conducted. Three of these focused on grey literature discussions around each of the three elements of the sectoral innovation system and one of these focused on academic literature. A sub-section of the desk review on institutional environment focused specifically on developing an understanding of the current policy landscape in South Africa. Semi-structured interviews ranging from 30 to 60 minutes were conducted with 22 individuals from academia (10 interviews), private sector (4 interviews) and government (8 interviews).

The qualitative data collected was codified in a series of interview notes/ full transcripts (where possible) and written notes of information found in written sources from the desk reviews. Data analysis of these took three forms. Firstly, the data collected was sifted to develop an excel spreadsheet outlining details of all the invention education and support programs that have been identified. Second, the data was read and re-read to pull out overarching themes relating to the research questions and the data inputted into a thematic matrix. This was then used to fill various sections of the final report.

A stakeholder validation workshop was also held following the drafting of the first round of the final report and involved 16 stakeholders from academia, government, and the private sector. During this workshop, the results of the project were presented. Comments and feedback on the results were received with a specific focus being given to the bottlenecks at various stages of the innovation lifecycle and the anomalies in the findings (e.g., that very few fintech projects were identified).

4. Study results

The study results are discussed against each of the three elements of the innovation system: knowledge and technology, actors and networks and, institutions. An overarching set of challenges and opportunities were also identified and are also introduced.

4.1 Knowledge and technology

There are two key documents produced yearly that provide a 'go-to' location for lists of 'new technologies' in South Africa, namely, the Technology Innovation Agency (TIA) and Council for Scientific and Industrial Research (CSIR) annual reports. For example, TIA produced 77 new technologies between 2015 and 2020 while CSIR recorded 48 new demonstrations in 2020-2021. A review of innovation, incubation and hacker spaces also highlighted a range of new digital technologies being developed and being at various stages of commercialisation. However, not all new technology that was listed in these reports was digital or high-tech i.e., R&D intensive. They also included new skin care ranges, environmentally friendly rat traps to new ways to fireproof housing and alternative methods to extract metals from waste materials; to name just a few examples.

In addition, the team conducted a frequency analysis on the reference to each technology across the desk reviews conducted. A total of 123 projects using emerging technologies were identified through the desk review. The frequency analysis results also fit with the list of technologies given to us by those interviewed. Table 1 outlines the top 10 results of this analysis, i.e., the technologies referenced the most as being the focus of attention of projects at various stages of the innovation lifecycle by either private sector or public sector actors. Thus, the results are split between the technologies mentioned in relation to public sector organisations and private sector firms in the grey literature and systematic academic literature review. The desk review did not identify every single government department, university or private sector company that works with, promotes, or uses emerging technologies in South Africa. However, we are confident given that we have captured data across 39 public sector and 82 private sector organisations that we have a list that is typical of the foci of South African organisations.

The list of foci technologies defined as emerging in respect to the public sector organisations differs from those of the private sector (see Table 1). The most frequently mentioned emerging technology in the private sector is next generation (next gen) medicine while this is number four on the list in the public sector. Top of the list in the public sector is 3D printing and artificial intelligence (AI). AI is fourth on the list in the private sector column and 3D printing down at number 6.

Table 1: List of top emerging technologies in South Africa

TOP 10 TECHNOLOGIES ACROSS PUBLIC AND PRIVATE SECTOR				
Emerging Technology		Frequency		
Next generation health		26		
Artificial intelligence		23		
3D printing		21		
Energy storage solutions		18		
Biotechnology		17		
Water purification technologies		13		
Hydrogen technologies		13		
E-commerce technologies		11		
Software/ mobile applications		10		
Next generation agro-processing		9		
PRIVATE SECTOR FOCUS		PUBLIC SECTOR FOCUS		
#	Emerging Technology	Frequency	Emerging Technology	Frequency
1	Next gen medicine	15	3D printing	15
2	E-commerce	11	Artificial intelligence	14
3	Software/ mobile apps	10	Biotechnology	11
4	Artificial intelligence	9	Next gen medicine	11
5	Energy storage solutions	8	Hydrogen technologies	10
6	3D printing	6	Energy storage solutions	10
7	Biotechnology	6	Next gen agro-processing	8
8	Water purification	5	Water purification	8
9	Energy generation solutions	5	New materials	5
10	Automation	4	Synthetic biology	4

Source: authors

The list includes many of the technologies included in the list of emerging technologies listed in the South African White Paper on Science, Technology and Innovation of 2019. This list of 'emerging fields of knowledge, technologies and materials that will shape the near future' (DST, 2019: 18) is made up of: graphene (new material), regenerative medicine and medical geology, carbon

capture and storage as well as modelling, simulation and gaming, quantum computing, artificial intelligence, and virtual reality.

It also maps onto the list developed by the African Union High-Level Panel on Emerging Technologies (APET), established in 2016. APET has identified and prioritized ten emerging technologies as priority areas of relevance for Africa's socio-economic development. These are: 1. Gene drives; 2. Microgrids (included under energy generation technologies in Table 1); 3. Drones for precision agriculture; 4. Next- generation medicine; 5. Artificial intelligence; 6. Urban agriculture 7. Synthetic Biology; 8. 3D printing; 9. Next-generation batteries (included in energy storage technologies in Table 1); and 10. Water purification.

Table 1 highlights that what is determined as 'emerging technology' is not always new technology or that which is heavily digital or high-tech i.e., R&D intensive. In fact, 15% of the papers that were read in depth for the systematic literature review focused on non-digital and non-high-tech solutions and deemed them 'emerging'. This included ICT technologies and farming techniques such as aquaponics.

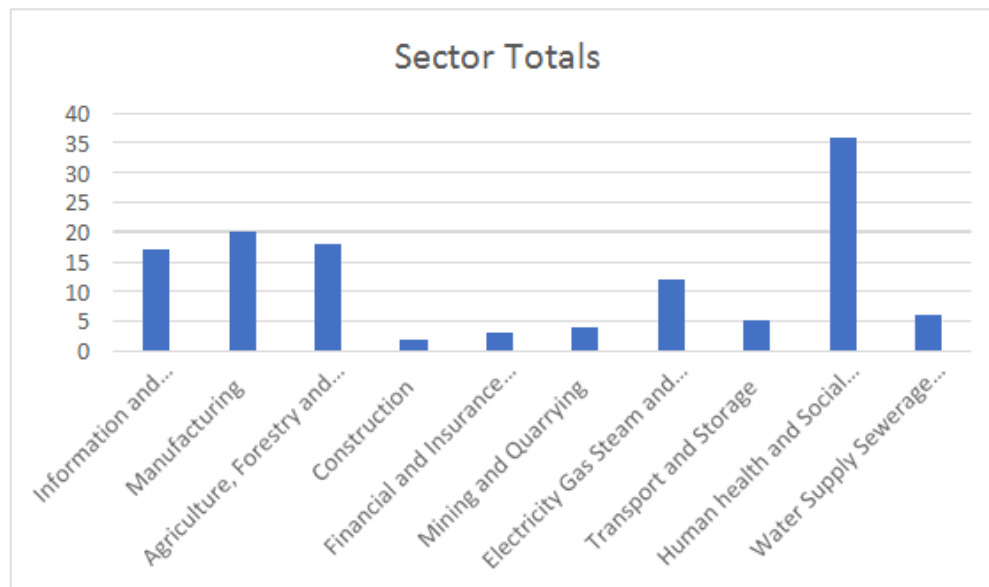
As noted by one interviewee (Interview 19) who worked in a field that spans biotechnology and next generation health (including diagnostic devices) asked:

"What is emerging technology? I mean, this [their company's technology] is based now on 20 years technology that is around... so I would say that part is already established, and we do some, some test development [of new technology]"

The technologies identified highlight the need to define 'emergence' as more than just something that is new to the world but also something that is new to a context. The focus of the private sector on technologies that may already be seen as established e.g., e-commerce and mobile/ software applications reiterates this. In addition, during the stakeholder validation workshop a discussion was held on the importance of considering the end products and services that are developed and used as opposed to the base technologies that are used to make the products and services.

When we look at the sectors in which these technologies and their resulting products and services are being used, Figure 1 provides an overview of the sectors in which the 123 projects identified are situated.

Figure 1: Distribution of emerging technologies by sector



Source: authors.

It is interesting to note that at least one interviewee noted the importance of not just considering the sector in which these emerging technologies were being used but also the need for these technologies in different sectors. This interviewee (Interview 4) noted that an important focus must be on how these technologies solve problems and address issues of food security, transport and security challenges faced by society. A second interviewee (Interview 8) made a similar argument about the need to focus not on listing the 'top technologies' but the top challenge areas that need to be addressed in society (energy, social integration, and sustainability issues).

On the issue of technical skills to develop the technologies, the range of opinions included:

- 'We have some good graduates and masters with knowledge [required]' (Interview 20)
- 'Not that no PhDs, just no opportunities' (Interview 11)
- 'We have to train on the specific technology but finding good people is not difficult in South Africa' (Interview 119)
- 'There are skills in research but not innovation within the commercial, private sector' (Interview 15)

This last sentiment about the skills being taught at universities was echoed by three other interviewees too. One interviewee noted that they had been looking to appoint a programmer for four months and the position is still vacant. He explained that the reason was not because there are no programmers in South Africa, but because their field of focus (additive manufacturing) is new and

emerging in South Africa and therefore, there is not a large base of experienced professionals to choose from.

There was a strong sentiment that there was insufficient support for PhD students to start their own businesses (spin outs from university). This is even though one interviewee noted that in South Africa any public sector organisation that conducts research and development must have a technology transfer office. Two interviewees noted that African universities have the wrong incentive structure in place with a focus on publications and not patents and commercialisation. Interviewees noted that the structures to support commercialisation were not just a problem in universities but that there were difficulties to commercialise products across the board (the valley of death situation).

A third of the interviewees discussed the pipeline issue for skilled staff. The private sector interviewees all noted that there were skills available, although one noted the need to train further. Several interviewees noted that, while there have been improvements in basic education and the teaching of science, technology, engineering, and math (STEM) in schools in South Africa – two interviews discussed the introduction of robotics and coding into the national education syllabus from 2023 – the knowledge was still lacking in comparison to other countries. One private sector interviewee noted that it was difficult to find staff to work for him with the skills he needed because they tend to have better opportunities abroad; that the country still suffered from brain drain.

Several interviewees also noted that private companies had started their own training programmes. Sasol and Eskom were named by interviewees as having sent some of their employees for PhD training because they realised they needed to upskill their internal capacity.

Finally, over a third of interviewees noted the need to not just train researchers and those working in business to develop the technology but also communities to use the technology. Data on digital skills from the World Economic Forum show that South Africa has a rating of 3.27. These are basic computer skills, basic coding skills and digital reading skills where 1=not all and 7 = to a great extent. This compares to Kenya at 4.55, China at 4.66 and the Republic of Korea at 4.99. From this, it can be deduced that the digital skills in South Africa are quite low. Interviewees specifically focused on the work of the department of telecoms and particularly, NIMESA (National Electronic Media Institute of South Africa) who provide digital literacy training to individuals and government staff. This links to a broader issue discussed by most interviewees with regards to the degree to which South Africa should be developing its own technology and just importing new technology from elsewhere.

4.2 Actors and networks

Through the desk review and interviews, the study team identified a diverse sample of 216 actors and networks in the emerging technology space, including firms, global development agencies, financiers and investors, and government departments, agencies, bodies, and state-owned enterprises. However, the prevalence, configuration, and contribution of actors in the different emerging technology clusters varies, reflecting, in part, perceived opportunities and the size and maturity of the sector (or sectors) in which the technology can be applied.

Universities and public research institutions are (and have been) active in both applied and basic research as well as teaching and learning. A list of 28 universities and other research entities involved in emerging technology research was developed from the desk review and interviews.

The role of several key state actors notably, the Department of Science and Innovation (DSI), the Council for Scientific and Industrial Research (CSIR), the Technology Innovation Agency (TIA) and the Industrial Development Corporation (IDC), is evident for advancing emerging technology development, uptake, and upscaling in South Africa. These agencies were seen as key to funding research and commercialisation of technologies (DSI, CSIR, IDC) but also to providing direction in the development of technologies. For example, one interviewee mentioned the development by DSI of a roadmap for 3D printing (the South African Additive Manufacturing Strategy published in 2016). Roadmaps for emerging technologies that have been developed in South Africa by these actors and others including: the waste to energy Roadmap; water research, development, and innovation roadmap and; hydrogen society roadmap.

Several interviewees mentioned the National Research Foundation (NRF) as being important for funding research at universities which often included the involvement of private sector actors in research consortia too. Line ministries were also seen as important in pushing innovation and technology development forward in these emerging technology areas (notably the Department of Health, Department of Trade, Industry and Competition as well as the Department of Agriculture, Land Reform and Rural Development).

State actors appear to have often played an early-mover role as research funders, investors and financiers, and developers of networks and alliances. However, interviewees differed in the degree to which they felt government should actively push innovation activities. One interviewee mentioned the Square Kilometre Array project as an example of the benefit of taking a mission-oriented approach to emerging technology development which builds specific capabilities in the country. Others noted that the 'red tape' to get funding and support complicated the usefulness of public funding (one

interviewee noted it took two years to get to prototype stage because of the paperwork involved).

Only two interviewees mentioned the role of provincial and municipal governments in the emerging technology field. One mentioned work by the City of Johannesburg to promote green technology. Another interviewee mentioned a collaboration between DSI, MLab (a non-profit mobile applications laboratory) and the Limpopo provincial government to promote agricultural and tourism innovation in Limpopo province (with funding from CSIR).

The private sector was mentioned by all interviewees as a key actor in these fields. Many interviewees noted that these emerging technology fields are not just the realm of large corporates but small and medium-sized firms as well as incubators and makerspaces. The industries that were mentioned most by interviewees as being engaged in emerging technology development or use were telecommunication firms, mining companies and banks/ insurance companies.

The desk review highlighted larger listed firms and multinationals have greater visibility when emerging technologies have applications in existing markets and/or require significant capital expenditure e.g., British producer Lonmin Plc (its operational headquarters are in Johannesburg) investing in additive manufacturing for jewelry. Conversely, smaller, newer, and unlisted firms appear to have had opportunities where markets for new technologies are not established. Examples here include ICT start-up Khula, creating apps for agriculture supply chains, the PACSys and DC Geomatics Joint Venture for precision agriculture utilising drones and AI for crop spraying.

Partnerships and collaborations were seen as essential, either to deal with funding gaps or to bring in capabilities where these were missing. Many of the university interviewees mentioned the importance of European research funding in this regard and its role in building the capability of local South African researchers. One interviewee mentioned the African Development Bank as a key funding partner for emerging technology innovation while others mentioned the expected funding partners notably, NRF, IDC and venture capital. The desk review also identified that CSIR hosts the South Africa 4IR Centre. This has an official partnership with the World Economic Forum and is part of a network of similar centres around the world. It has a governmental remit to promote and develop governance and policy frameworks to enable South African businesses and government departments better take up, utilise, and regulate these emerging technologies.

South Africa is part of many global collaborations with the following specific to emerging technologies: African Biosafety Network of Expertise (ABNE), African Biosciences Initiative (ABI), NANOsciences AFrican NETwork

(NANOAFNET) and SmartAfrica. The team identified 17 different partnerships and collaborations which covered many of the emerging technology areas identified in Table 1 notably 3D printing, agro-processing, drones, and artificial intelligence.

4.3 Institutions

This section focuses on the rules, norms and practices that support or hinder emerging technology development. It starts with a focus on policy attention and national narratives before moving to focused discussions on incentives and support systems, regulation (including risks, harm, and security issues) and funding for emerging technology.

4.3.1 Policy narratives

The South African government has focused significant attention on a particular set of emerging technologies related to the 4IR. This is illustrated by the appointment in 2019 of a Presidential Commission on the Fourth Industrial Revolution (PC4IR). The 30-member Commission pulled together experts across different sectors of society to assist the government in taking advantage of the opportunities presented by the digital industrial revolution. Chaired by the country's President, the Commission identified a set of priorities, strategies, and action plans to position South Africa as a competitive global player in 4IR. The PC4IR report was published in 2020 and had eight areas of recommendations:

1. Investment in human capital
2. The establishment of an artificial intelligence (AI) Institute
3. The establishment of a platform for advanced manufacturing
4. To secure and avail data to enable innovation
5. Incentivise future industries, platforms, and applications of 4IR technologies
6. Build 4IR infrastructure
7. The review and amendment (or create) policy and legislation
8. Establish 4IR Strategic Implementation Coordination Council

It is noticeable that it has focused deliberate attention on two core emerging technology areas: artificial intelligence and advanced manufacturing.

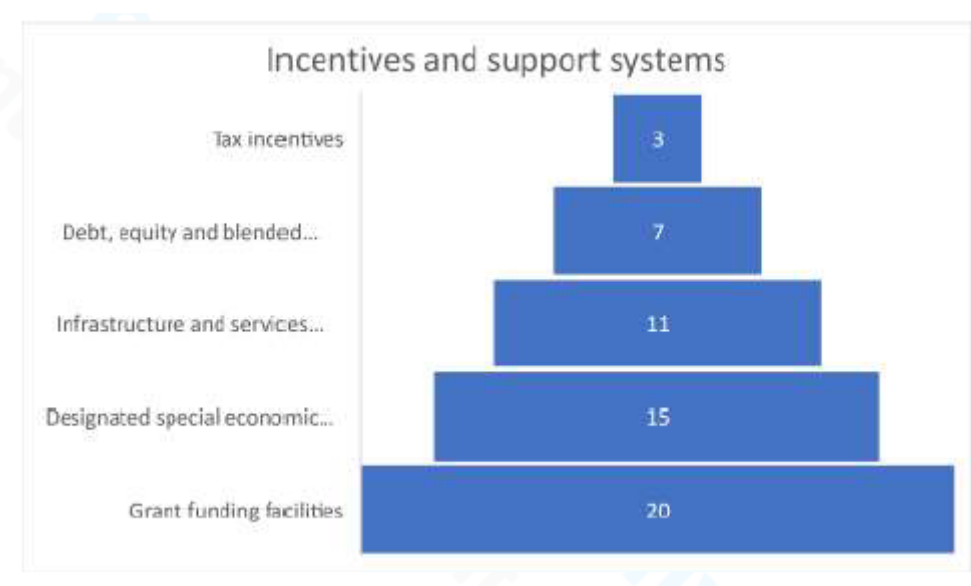
While the Department of Communications and Digital Technologies is tasked with implementing the PC4IR report recommendations, we found several line ministries have started efforts to engage with digital and 4IR technologies. For example, the Department of Health set out a National Digital Health Strategy (2019-2024), the Department of Economic Development and Tourism (DEDAT) launched a Dash-Tech programme in the Western Cape to strengthen the technology start-up and the Department of Home Affairs (DHA) has taken a

centre-lead approach in embracing the 4IR and a digital strategy (White Paper on Home Affairs, 2019) moving many of its activities online or integrating with technology (White Paper on Home Affairs, 2022). In addition, the Department of Arts and Culture (DAC) is committed to embracing the 4IR and emerging technologies (Revised White Paper on Arts, Culture and Heritage, 2017).

4.3.2 Incentives and support systems

The South African government has implemented various incentives and support systems for firms through government departments, bodies, and agencies. These include financing and grant funding facilities, tax incentives, and access to infrastructure and services (see Figure 1).

Figure 1: Emerging technology incentives and support systems available in South Africa



Source: authors

Three tax incentives were found to exist in South Africa. The best-known is an R&D Tax Incentive administered jointly by the DSI, South African Revenue Service and Treasury. The incentive was initially implemented in 2006, under Section 11D of the Income Tax Act, 1962, and has since continued to evolve. The other two tax incentives are not specific to R&D but are focused on providing incentives to businesses that could be helpful to those focusing on emerging technology development or deployment. Specifically, the 12R special economic zone (SEZ) tax incentive (providing reduced tax rates for those operating in an SEZ) and 12L tax allowance for those developing green- and brown-field sites using energy-efficient technologies. Furthermore, S12B(h) of the Income Tax Act provides a rebate on purchasing equipment to produce renewable energies.

Other incentives available include debt, equity, and blended finance facilities. Most of these again are not specific to emerging technologies apart from TIA's sector funding which is focused partly on emerging technology sectors including ICT and advanced manufacturing.

Infrastructure and support services available are provided in a range of areas, notably generally in entrepreneurship and business development. The Enterprise Supplier Development (ESD) programme incentivizes companies that offer training and development to small supply chain and ESD partners and participants. The programme is one of the country's largest funding drivers for innovation incubators and hubs allowing for R12 billion in capital to be generated for empowerment initiatives (OC&C & Google, 2018). As noted above during interviews for this report, several interviewees emphasized the government-based organisation, National Electronic Media Institute of South Africa (NEMISA), labelling it as a significant institution responsible for the development and promotion of emerging technologies in the country. Interviewee 5 stated that NEMISA provides incentives for emerging technology adoption and offers training to intermediaries in several communities, further making specific funding allocations to institutions, such as universities, where there is a focus on digital transformation skills development.

In addition, the interviewee also highlighted that many universities focus on skills development in local communities which is an incentive to local government. The CSIR has specific services and support available focusing on a several emerging technologies including biomanufacturing and biorefinery technologies, clean tech, nanotech, and photonics. This support includes the provision of R&D and testing facilities as well as support to commercialise new technologies.

South Africa has invested in special economic zones to promote the development of businesses and external investment. Several of these are focused on assisting companies working in the following emerging technology areas: green tech (Atlantis SEZ); next-generation farming (Coega IDZ and Dube Agrizone) and next-gen medicine/ medical manufacturing (Gauteng Medical Manufacturing Cluster).

The largest area of support and incentives for emerging technology research, development, and deployment that we have identified through the desk review relates to grants. None of these, however, are specifically focused on emerging technologies per se but are general grant funding opportunities for business development, often with a sectoral focus.

4.3.3 Regulation, risks, harm, and security

The National Planning Commission (NPC,2020) acknowledged the need for more regulation of digital technologies and recommended that an overarching

policy or regulatory framework should be implemented for the use of 4IR technologies in its entirety rather than individual policies for each new technology. The NPC also recognises the need for an 'integrated infrastructure plan' so that the basic building blocks relating to light, power, water, roads/transportation to assist technology development and deployment are available. A third of interviewees noted the importance of what they termed 'skeleton technologies,' 'backbone technologies' or basic infrastructure needed to support the development of emerging technologies. Some incorporated human resources and skills within this grouping and others separated it out.

To support the development of technologies and innovation, South Africa has the following Acts relating to intellectual property and protections:

1. Intellectual Property Rights from Publicly Financed Research and Development Act 51 of 2008
2. National Environmental Management: Biodiversity Act 10 of 2004
3. Patents Act 57 of 1978
4. Merchandise Marks Act 17 of 1941
5. Copyright Act 98 of 1978 (and Copyright Amendment Act, 2018)
6. Designs Act 195 of 1993
7. Plant Breeders' Rights Act 15 of 1976
8. Trademarks Act 194 of 1993

The first of these specifically focuses on clarifying who owns intellectual property (IP) that is developed within publicly funded organisations in South Africa. It also mandates that the owners of the IP commercialise and utilize the IP for the benefit of the South African society. More recently the government has affected the first phase of an IP policy for South Africa that aims to provide direction across these eight different legislative Acts. The first phase is focused on ensuring South Africa's IP regime is fit for purpose against international standards and is focused on the area of medicines and health. Phase II will look at copyright and other areas.

In addition, while there was no major mention by government agency interviewees or the private sector of internal policies that support and incentivise innovation in emerging technologies, there was recognition in the academic community interviewees of the existence of policies, standards and regulations within universities and research institutes that dictated how emerging technology R&D and commercialisation took place. Key among these and most often commented on was organisational level IP rules. A key focus of interviewees was the need for clear, consistent, and simple regulations and policies. Two quotes exemplify the type of comments received:

"For instance, as an example, given the issue of Blockchain with respect to special cryptocurrencies, we don't have a clear legislation..." and "So the application of genome editing within the agricultural field should have been so

simple and quick. But we're still fighting about the regulations. So, the regulations are definitely one of them." (Interview 11)

"For example, SA did develop an EV about 14 years ago, but policies were not in place to support the production of it and the project died" (Interview 14)

With regards to risk, there are two parts to this discussion that should be mentioned. The first is the risk appetite of investors and entrepreneurs. Most interviewees believed the risk appetite in South Africa was low but that only those who had an appetite for risk would invest in these technologies, given the uncertainty of their futures. However, also noted in the desk review (and interviews) has been the lack of strong and reliable infrastructure and corruption.

The second area of risk relates to the risks and harms from emerging technologies. South Africa has done most here in relation to technologies that are digitally focused. For example, the Cybercrimes Act 19 of 2020 was enacted with several aims intending to create a greater offence around cybercrime, to regulate the jurisdiction in relation to cybercrimes and the powers to investigate it; to impose obligations to report cybercrimes; capacity building; to enter agreements with foreign statements for the detection, mitigation, prevention and other matters related to cybercrime. To ensure data protection, the Protection of Personal Information Act (POPIA) was implemented. Commenced on 1 July 2021, the Act seeks to protect citizens from his/her confidential information being accessed, used, and shared without consent. It is also focused on limiting fraudulent activities, identity theft and general protection of information.

There have been some attempts to review the risks and harms to the public of these emerging technologies in South Africa. For example, a 2019 working paper (Goga and Paelo, 2019) reviewed the opportunities and barriers of e-commerce in South Africa and recommended the need for a unified strategy for e-commerce in South Africa. An overview of the potential risks to jobs, the planet, human health, and increasing inequality that were identified through the desk review and interviews is presented in Table 2. It should be noted that those listed here are all negative risks, however, the PC4IR noted that the risks can be mitigated and not embracing 4IR technologies (as one element of emerging technologies) would pose a risk of South Africa losing its economic competitiveness. One interviewee who was on the PC4IR commission noted that the issue of 4IR technology as a risk to jobs was one of the key issues discussed during the Commission's activities.

Table 2: Risks of emerging technologies

Risk type	Summary
JOB	Puts traditional jobs at risk Exacerbates a skills mismatch existing in the country Use of 4IR in other countries results in movement of industry to other countries resulting in job losses
PLANET	Plundering of scarce resources with knock-on effects to local communities where here is inadequate regulation Energy use of new 4IR technologies is significant and detrimental of this comes from fossil fuels
HUMAN HEALTH	Serious illness is possible from the heavy metals and compounds associated with e-waste in unregulated landfills New workplace health, safety and environment hazards created from new technology development e.g., additive manufacturing Various psychological and physical implications of the ‘dark side’ of digital technologies related to issues such as cyberstalking and online fraud.
INCREASING INEQUALITY	Existing power dynamics and inequalities can be exacerbated and strengthened by emerging technologies if these technologies are not made affordable and accessible to the poorest and marginalised in society.

Source: authors.

4.3.4 Funding

Interviewees noted funding as a key enabler or barrier to the development of emerging technologies in South Africa. In the South African National Survey of Research and Experimental Development 2019/2020, government funding accounted for 56.3% of national research and development funding while the business sector contributed 27.1% (CeSTII, 2021). Total national expenditure on research and development in 2019/2020 was R36.784 billion, a 5% decrease from the R38.725 billion reported in 2018/2019.

Table 31: Funding for research and development by source (2010/11 to 2018/2020)

YEAR	TOTAL FUNDS	GOVERNMENT*	BUSINESS	OTHER SOUTH AFRICAN SOURCES**	FOREIGN SOURCES
	R'000	R'000	R'000	R'000	R'000
2010/11	20 253 805	9 018 874	8 128 246	661 676	2 445 009
2011/12	22 209 192	9 561 917	8 663 105	653 674	3 330 496
2012/13	23 871 219	10 831 893	9 152 042	770 300	3 116 984
2013/14	25 660 573	11 007 083	10 615 902	722 361	3 315 227
2014/15	29 344 977	12 873 458	11 981 974	923 530	3 566 015
2015/16	32 336 679	14 425 992	12 578 499	1 122 328	4 209 861
2016/17	35 692 973	16 427 596	14 045 892	1 047 980	4 171 507
2017/18	38 724 590	18 082 182	16 066 846	638 858	3 936 705
2018/19	36 783 968	17 475 173	14 534 123	775 938	3 998 734
2019/20	34 484 862	19 416 933	9 358 770	1 046 861	4 662 299

*Includes science council and university own funds.

**Includes funds from higher education institutions, not-for-profit organisations and individual donations disbursed to all sectors.

Source: Reproduced from CeSTII (2021, p. 12)

According to a Partech Partners Africa Tech Venture Capital report (Assou et al. 2022), in 2021 South Africa attracted US\$832 million of equity funding in 132 deals. FinTech dominated in terms of resource allocation, followed by Health Tech, enterprise (early stage), and EdTech. Linking finance flows to private actors or specific technologies is, however, challenging with many firms only partially disclosing funding (often in press releases) or keeping details confidential.

There is better transparency with government funding and development agencies. For example, the state-owned Industrial Development Corporation (IDC), whose sectoral remit includes Agro-processing and Agriculture, Automotive and Transport Equipment, and New Industries, publishes quarterly disclosures of IDC funded business partners (e.g., IDC 2021). The IDC plays a significant role in funding industry and project development in key sectors aligned to the National Development Plan. In 2021, it established a R1 billion fund in partnership with the Department of Agriculture, Land Reform and Rural Development to support agri-industrial development (IDC 2021), while reporting a R336 million investment in clothing and textiles competitiveness and R10.6 million in agro-processing. The desk review identified 20 partially disclosed individual transactions which included funding for start-ups but also for financing established technology/ companies. It included funding for trials and prototyping as well as scaling funding. In some cases, it also included funding for infrastructure.

This is interesting given that the findings from interviews confirm the availability of funding but that there is insufficient funding at the commercialisation stage. Interviewee 16 noted:

“And I think that helps (referring to funding R&D). On the other hand, we found that the difficulties for us is when you get to commercializing this technology. The support seems to be much less. And we actually end up self-funding what we're doing currently.”

Interviewee 16 highlighted the importance of funding the whole value chain of technology development. He added that lack of funding at commercialisation stage for example, leads to the development of technology in the country but implementation elsewhere. Interviewee 14 gave an example of this with Desalination, which he said is a technology developed in South Africa but adopted by Israel companies who are profiting from it in other countries. This leads to a missed opportunity in solving South Africa’s own socio-economic challenges with our own technologies.

Academic interviewees echoed the sentiments that there is controversy surrounding funding, most highlighting that there is a lack of funding available. While many academics hear of the same few organizations and similar projects that are made available (Interviewee 6). Therefore, it provides the impression that calls for funding are not advertised widely to the public. Interviewee 7 highlighted several projects and many of high value that have received funding from TIA and DSI numerous times. Interviewees 4 and 6 stated that they were not personally aware of funding opportunities but have heard of colleagues in other departments or at other universities that have frequently received grants.

4.4 Challenges and opportunities

During the desk review and interviews a number of challenges and opportunities for emerging technologies in South Africa were identified across the three innovation system elements. These are outlined in Table 3. Not included in Table 3 because it spans across all three elements is the broad issue of ‘barriers to entry’ which are higher for some technologies than others. One example noted during the stakeholder validation workshop being the differences between innovating in the biotechnology space as opposed to the digital technology (mobile apps) space.

Table 3: Challenges and opportunities facing emerging technologies in South Africa

	CHALLENGES	OPPORTUNITIES
TECHNOLOGY AND KNOWLEDGE	• Debate around the ability of South Africa to develop its own technologies and the relative merits of taking technology from elsewhere and contextualising it. • Lack of skills especially on the user end i.e., simple	• Training and knowledge around emerging technology are increasing e.g., school syllabus will include coding and robotics from 2023 and SETAs are increasingly providing training on 4IR technologies.

	CHALLENGES	OPPORTUNITIES
	digital skills and awareness. • Infrastructure issues and access to skeleton or backbone technologies. Relatedly, the importance of general purpose technologies such as electricity • Incentive structure in universities and brain drain limit the levels of innovation (and commercialisation of) emerging technologies. • Still some deficiencies in the pipeline for researchers and staff for technology development companies.	• Universities have begun taking emerging technologies into account and including teaching into their curriculums, both formal and CPD/ short learning programmes. • Likewise, companies are realizing the importance of training and upskilling of staff and have introduced training programmes. • The opportunities availed from coupling and convergence of technologies i.e., combinations of technology today.
ACTORS AND NETWORKS	• Despite some evidence of partnerships and collaboration, gaps remain especially creating a 'valley of death' between development and commercialisation stages of these technologies.	• Government attention is currently focused on 4IR, one significant part of the emerging technologies list. • Role of SMEs as well as large firms and multinationals in this space. • Evidence of partnerships and collaboration, some involving the private sector. South Africa involved in important regional initiatives on emerging technologies.
INSTITUTIONS	• Deindustrialisation and decay of physical infrastructure creates lack of risk appetite especially for foreign investors. • While policies and regulations exist, they are often cumbersome and unclear creating confusion and again, reducing interest of actors to become involved. • Funding and incentives do appear to be available but not often dedicated to the emerging technologies that are the focus of attention in South Africa; many are focused on entrepreneurship and business development generally.	• Government policy to promote emerging technologies notably mentioned in the White Paper on STI of 2019. • Universities increasingly have policies and programmes in place to promote innovation and entrepreneurship. • Recent decision to develop an IP policy for South Africa aims to make IP legislation more facilitatory and in line with international legislation.

Source: authors.

A key issue that has not been adequately discussed in previous sections but was raised by interviewees and requires special attention relates to the degree to which South Africa should be developing technologies. This would be instead of importing them and contextualising these to the needs of South Africa. One interviewee put this very strongly:

"...I don't think we should even try to second guess what the rest of the world is doing... let's be honest, we shouldn't. We should quite happily just accept frontier technology from India, China, the US, Europe, etcetera for us to reinvent wheels. It would be putting our energy in the wrong place, so we should not be reinventing. ...we should be focusing our energy on how to put new technology to work in a South African and an African context. That is where our focus should best be in that can be done in partnership with the global tech providers, because we can be a good proving ground for applications of emerging technology."

A key argument related to this was the pipeline issue (not having enough technical people in new emerging technologies yet vs. the more established emerging technologies). The other related argument used was that South Africa is unable to commercialise technology sufficiently because of a low-risk appetite and/or lack of funding.

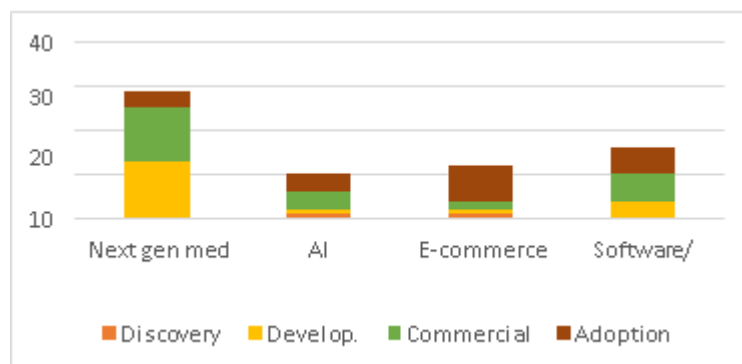
5. Discussion

The full discussion of the study's results is available elsewhere (REDACTED FOR PEER REVIEW). However, we would like to focus our discussion on two key findings that emerge from the empirical results. First, is the need to not define emerging technologies immediately with digital or the latest technologies. The characteristic of radical novelty in a developing country context must leave room for other forms of technology that are radical and new to an environment (not necessarily just new to the world). A key example here is both water purification technologies (e.g., new forms of microfilament material) as well as some next-generation agro-processing technologies (e.g., hydroponics). Both technologies are listed in the top ten emerging technologies based on the data we reviewed and feedback from interviewees as well as the stakeholder validation workshop.

It is important that these technologies are not ignored in policy settings because of the dominant narrative in South Africa but also in other countries towards 4IR technologies and emerging technologies that are digital in focus. As these emerging digital technologies take hold, notably artificial intelligence, and become seen as a general-purpose technology, it will be important to not forget these other technologies. They might not have the ability to be classified as general-purpose technologies, but they do have a key role to play in economic and social development trajectories of society.

Related to this, the findings highlight the existence of two other ways of thinking about emerging technology which we term ‘new emerging’ and ‘waning emerging technology’ in the main study report. This relates to the fact that we found textual discussion and interviewees talking about emerging technologies at different stages of the innovation lifecycle. From the list in Table 1 of the Top 10 emerging technologies identified across the public and private sectors we identify two top new emerging technologies: artificial intelligence and next generation health. These have the highest numbers of projects identified across both the public and private sector and have less activity at the adoption stage of the lifecycle relative to other stages (see Figure 2); hence the framing as ‘new emerging technologies’. By comparison, e-commerce, and software/ mobile application technologies, while not having as many projects across the innovation lifecycle were found to have the highest number in the adoption phase of the lifecycle. As such we suggest referring to these as ‘waning emerging technologies.’ These technologies can be seen as becoming what are known as ‘general purpose technologies’ (Agrawal et al, 2023; Bresnahan, 2019; Cockburn et al, 2018; Trajtenberg, 2018) or core technologies that have uses across multiple sectors and form a critical base technology for other technologies to build onto.

Figure 2: Top new and waning emerging technologies by projects at lifecycle stages



Source: authors.

Being open to a broader understanding of the distinct types and stages of emerging technologies may go some way to addressing the comment by several interviewees as to the need for technologies to be focused more on solving problems or challenge areas affecting the country and societies in Africa.

The second major empirical result to be mentioned here is related to the lack of dedicated policies and strategies to support technology emergence in South Africa. That said, South Africa has a mature policy space in STI policy. It has recently (2019) updated its White Paper on STI, it has had a Presidential Commission on one set of emerging technologies (those related to the 4IR) and

it has started to address deficiencies in its IPR legislation starting with the first phase of an IP policy development and implementation.

There have also been some attempts to develop technology specific strategies or roadmaps including those focused on 3D printing (e.g., the South African Additive Manufacturing Strategy), the waste to energy roadmap, water research, development and innovation roadmap and hydrogen society roadmap. There appears to be no comparable document for next generation health although CSIR have a programme cluster with an internal plan focusing on next generation health. Similarly, the analysis has not found a country level AI strategy or roadmap although the SmartAfrica initiative is developing a blueprint for AI for the continent.

Specifically, there are no apparent roadmaps or strategic plans to guide the development of the top four emerging technologies identified (artificial intelligence, next generation health, mobile applications, and e-commerce). This is despite a significant level of activity taking place in these areas and a plethora of actors being involved.

Finally, the study has provided an opportunity to reflect on ideas around systems of innovation and the boundaries of these systems. It has specifically enabled us to consider the usefulness of sectoral innovation systems in a context where sectors in relation to technology use could be becoming more and more difficult to define given the focus being placed on the potential general purpose nature of several emerging digital technologies, notably artificial intelligence. This topic has already been recognised and a whole special section of *Industrial and Corporate Change* in 2021 devoted to it (Li et al, 2021).

Malerba (2002) notes that, while there is a set of literature that has looked at sectors more broadly, in economics, sectors have traditionally been considered in terms of industries which are static and bounded by their similarities in techniques and demand. Thus, Malerba defines a sector as a “set of activities which are unified by some related product groups for a given or emerging demand and which share some basic knowledge. In a sector, firms have commonalities and at the same time are heterogeneous.” (Malerba, 2005). He argues that “interdependencies and complementarities define the real boundaries of a sectoral system. They may be at the input, technology or demand level and may concern innovation, production and sale.” (Malerba, 2002).

Li et al (2021) note however that “the new wave of social-technological changes since the new Millennium has been largely reshaping sectoral systems” with consequences for how sectors are defined, operate, and are managed. The papers in the special section elucidate the complexities brought about by these new and increasingly general-purpose technologies but do not go into depth on the implications for still focusing on ‘sectoral innovation systems.’

That said, what this special section, and our study bring out is the increasing importance of viewing innovation support and analysis from a systems approach given the increasing interconnections across sectors. Despite critiques of innovation systems thinking (e.g., Schot and Steinmueller, 2018), the approach still has analytical value.

Our study did not provide specific evidence on the value of bounding the innovation system in the context of these cross-sector technologies at national level (a la Lundvall, 1992). In fact, what evidence there is highlights the international nature of knowledge collaboration and technology transfer. Interviewees noted the reliance on imported technologies as opposed to local capabilities to develop and manufacture in country while others noted the importance of international (knowledge) collaborations. In a similar vein, Lee and Gereffi (2021) highlight the cross-national and cross-sectoral nature of smartphone technologies which utilize the emerging technologies identified by our study. Gereffi and colleagues work on global value chains more generally reiterates this.

The increasing dominance of emerging (digital) technologies that operate across traditional sectoral boundaries brings to the fore the idea of 'technological innovation systems' (Carlsson and Stankiewicz, 1991; Hekkert et al, 2007). The relative merits of utilizing this approach to study the innovation system of emerging technologies as opposed to the sectoral approach requires further attention.

6. Conclusion

This paper has outlined the results of a study of the innovation system landscape of emerging technologies in South Africa. It has outlined the differences in terms of emerging technologies that were identified and made a call for a more nuanced understanding of emerging technologies that takes account of the technological specificities (digital, non-digital), lifecycle stage and context of developing economies. A revised and more nuanced definition of emerging technologies or tiering of emerging technologies would help ensure that the debate on emerging technologies is not dominated by a particular interest area (e.g., 4IR technologies) and that a broad spectrum of technologies receive attention.

The paper has also highlighted the difficulties South Africa is facing in the policy sphere with regards to regulating and facilitating these technologies. The study results point to the need for more attention being given to the use of roadmaps and strategies to guide the development and diffusion of emerging technologies and sectors utilising emerging technologies.

Finally, the paper utilised a sectoral innovation systems analysis for a study that was not obviously sectorally focused in the classic industrial sector sense.

This is based on the flexibility of the definition of a sector given by Malerba (2002, 2005) but also because of the simplicity – for a policy focused study – of the three element analytical framework put forward to by Malerba in his 2005 paper. The paper highlights the importance of innovation systems frameworks for emerging technologies that cross sectoral boundaries and highlights the need to consider the definitions of a sector in this new technology driven world. As such, it continues a debate on the future of sectoral innovation systems already started by Li et al (2021) and adds a series of further questions to the debate.

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Note

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Regenerative medicines in Africa: The ethical imperative for an innovative regulatory framework

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Abstract

This paper shows that some degree of clinical research activities in the domain of regenerative medicine (RM) is increasingly going on in some parts of Africa. Besides these, patients in Africa with certain chronic diseases are targeted by online clinics and businesses who market unapproved RMs products. The absence of legal regulatory frameworks plays a central role vis-à-vis RM tourism. The different forms of harms (medical, fiscal, psychological) that patients who receive unproven RMs face, however, necessitate a prompt and pragmatic response. Drawing from data obtained from 20 African countries from the different poles/regions of the continent, this paper argues that there is an ethical imperative for countries in Africa to bridge the extant regulatory vacuum and develop an innovative regulatory instrument to stimulate research and development. Such regulatory frameworks will help prevent the exposure of patients to unapproved and unlicensed RM therapies that are increasingly being targeted wt patients with genetic and chronic conditions.

Keywords: Africa; Innovation; Regenerative medicine, Regulation; Stem cells.

1. Introduction

The emerging interdisciplinary field of regenerative medicine (RM) offers innovative therapeutic approaches to the treatment of chronic diseases, genetic disorders, and malignant conditions. This is accomplished through the augmentation, repair, or replacement of human body —parts such as genes, cells, tissues, and organs. While some African countries have begun conducting clinical trials (CTs) of some RM therapies, countries in the Global North (e.g., USA, Canada, and Germany) and selected countries in Asia (e.g., Japan, South Korea, and China) have made unprecedented advances that have been translated their clinical research efforts into the development of RM products/drugs.

That Africa still lags much behind in the field, with RM therapies still in a very early phase (Alaribe & Motaung, 2019), however, offers BioCompanies and BioPharma with developed RM products a viable market; especially since the African regulatory landscape for RMs is generally undeveloped. The regulatory vacuum equally offers online businesses and some Biotech companies who specialize in marketing unlicensed and unapproved RMs to patients in Africa. Unapproved RMs (e.g., cellular and genetic therapies) are treatments/drugs that have not received FDA (or equivalent regulatory agencies in respective countries) approval (Guleria *et al.*, 2022). The peddling of unapproved and unregulated RMs, however, potentially exposes such patients to different forms of medical, psychological (due to failed treatments), and fiscal harms.

Against this background, this paper argues that there is an ethical imperative for African countries to bridge the extant regulatory vacuum and develop innovative regulatory instruments to stimulate research and development in RMs, while protecting the public health. It suggests some of the regulatory

2. Methods

2.1 Conceptual framework

Innovation, in the context of healthcare, involves products, processes or structures (Varkey *et al.*, 2008). Therefore, processes or structures that enhance or generate newer healthcare - products such as drugs, vaccines and services can be deemed innovative because they will enhance the availability of such products and people's access to them (Berger *et al.*, 2010). Since innovation as a joint production process seeks the creation of new ideas, skills and competences (Lundvall, 2009) and the success of innovated products is shaped and influenced by the nature of the social gaps they seek to fill (Afolabi, 2013), regulatory frameworks generated in response to unmet needs should be essential avenues through which critical innovation should in healthcare.

This paper uses this framework. Specifically, it argues that the current regulatory lapses and vacuum that exist in RMs across African countries necessitate developing a regulatory process that will ensure the safety and efficacy of RM products tested via clinical trials, produced by local BioCompanies or imported into the continent.

2.2 Quantitative data

Three different approaches were used to generate the data that underpin the arguments made in this paper.

2.2.1 Step 1

To have a representative picture of the nature and trajectory of RMs across Africa, four countries were selected from each of the five poles/regions (North Africa: Tunisia, Egypt, Morocco, and Algeria; Western Africa: Nigeria, Ghana, Senegal, and Côte d'Ivoire; Eastern Africa: Ethiopia, Uganda, Rwanda, and Kenya; Central Africa: Cameroon, Gabon, Angola, and Republic of Congo; and Southern Africa: Botswana, Namibia, South Africa and Lesotho) of the African continent. A combination of each country name and keywords specific to RMs (stem cells, cell therapy, mesenchymal stem cells, gene modified therapies, and tissue engineered products) were used to search through clinicaltrials.gov and pactr.samrc.ac.za to get a list of the registered interventional RM-based CTs (early Phase I to Phase IV) that are associated with each country. A search for each country is also made through the PharmaIntelligenceCenter to see if there is any registered/licensed RM product associated with each country.

2.2.2 Step 2

Using academic databases (Cochrane, Google Scholar) a search was made to check for reported incidences of the use of unproven RM therapies in each of the 20 countries. In addition, a search was made to see if there are online clinics targeting patients in each of these countries.

2.2.3 Step 3

For countries where there is at least one registered RM-based clinical trial, the national gazettes and extant drug regulatory documents were obtained and systematically checked to see if they contain any provisions for the regulation of regenerative medicine therapies.

3. Results

3.1 RM-based clinical trials across African countries

Table 1 presents an overview of the RMs CTs. It shows that of all the 20 African countries, only 4 have some level of clinical research activities going on in the

area of regenerative medicine research and development, with the highest level being in the Northern region.

Table 1: Overview of RM-based Clinical trials across Africa

African pole	Country	RM-based CT or RM product	Highest Clinical Development Stage of the RM CT
Western Africa	Nigeria	0	NA
Western Africa	Senegal	0	NA
Western Africa	Ghana	0	NA
Western Africa	Côte d'Ivoire	0	NA
Central Africa	Cameroon	0	NA
Central Africa	Republic of Congo	0	NA
Central Africa	Angola	0	NA
Central Africa	Gabon	0	NA
Eastern Africa	Ethiopia	0	NA
Eastern Africa	Kenya	0	NA
Eastern Africa	Uganda	1	Phase II
Eastern Africa	Rwanda	0	NA
Northern Africa	Tunisia	1	Phase II
Northern Africa	Egypt	23	Phase IV
Northern Africa	Morocco	0	NA
Northern Africa	Algeria	0	NA
Southern Africa	Lesotho	0	NA
Southern Africa	South Africa	3	Phase III
Southern Africa	Botswana	0	NA
Southern Africa	Namibia	0	NA

Tables 2-4 present in-depth insights into specific RM therapies, the clinical diseases or conditions for which they are being evaluated, and the clinical development stage in the four countries.

Table 2: RM-based CTs in Egypt

RM type or product	Company	Clinical disease	Clinical development stage
Autologous mesenchymal stem cells	University-sponsored	Premature ovarian failure	II
Autologous stem cells	University-sponsored	Age-related macular degeneration	II
Autologous mesenchymal stem cells	University-sponsored	Premature ovarian failure	II
Autologous mesenchymal Stem cells	University-sponsored	Premature ovarian failure	II
Mesenchymal stem cell exosomes	University-sponsored	Type 1 diabetes mellitus	III
Autologous stem cells	University-sponsored	Idiopathic and drug-induced premature ovarian Failure	II
Autologous stem cells	University-sponsored	Azoospermia	II
Mesenchymal stem cells	University-sponsored	Male infertility	II
Autologous mesenchymal stem cells	University-sponsored	Defects of articular cartilage (e.g., degenerative arthritis, chondral and osteochondral defects)	III
Mesenchymal stem cells	University-sponsored	Stress urinary incontinence	III
Peripheral stem cells	University-sponsored	Retinoblastoma	III
Adipose-derived stem cells	University-sponsored	Androgenetic alopecia	IV
Platelet-rich fibrin	University-sponsored	Pulp necrosis	II
Autogenous platelet-rich fibrin	University-sponsored	Periodontitis	III
Myoblast transplantation	University-sponsored	Urinary incontinence	II
Autologous mesenchymal stem cells	University-sponsored	Pediatric fecal incontinence	II
Platelet-rich fibrin	University-sponsored	Periodontal regeneration	II
Injectable platelet-rich fibrin	University-sponsored	Acceleration of orthodontic tooth movement	III
Intra-articular platelet rich fibrin	Hospital-sponsored	Low back pain	IV
Platelet-rich fibrin	University-sponsored	Free gingival graft	IV
Injectable platelet-rich fibrin	University-sponsored	Gingival pigmentation	IV
Advanced platelet-rich fibrin	University-sponsored	Adult periodontitis	IV
Autologous Platelet-rich fibrin	University-sponsored	Odontogenic maxillary cysts	IV

Of the 23 RM-based CTs in Egypt, 6 are in Phase IV, 8 are in Phase III, and 11 are in Phase II of the clinical stage of development. Most of the trials are sponsored by Universities, or Tertiary Hospitals affiliated with Universities.

Table 3: RM CTs in Tunisia and Uganda

RM therapy or product	Country	Company	Clinical disease	Clinical development stage
Autologous peripheral blood stem cell	Tunisia	Centre National de Greffe de Moelle Osseuse	Multiple myeloma	III
Autologous adipose-derived stem cells	Uganda	Makerere University	Keloid	II

Table 4: RM CTs in South Africa

RM therapy/product	Company	Clinical disease	Clinical development stage
Fitusiran	Sanofi	Hemophilia A and B with inhibitors	III
Fitusiran	Sanofi	Hemophilia A and B without inhibitors	III
Fitusiran	Sanofi	Hemophilia A and B with or without inhibitors	III
OAV101 (Onasemnogene abeparvovec)	Novartis	Type 2 spinal muscular atrophy	III

Only 4 RM-related interventional CTs are associated with South Africa, all of which are in Phase III; while just one Phase II RM-based CT was associated with Uganda and Tunisia.

3.2 Unproven & unlicensed RMs across African countries

Unapproved and/or unregulated RM-based therapies such as stem cell treatment were found to be available in clinics, or through websites (for agents or foreign clinics) that would facilitate the travel of interested patients. Table 5 lists the selected African countries where such services were found, though traceable websites (Appendix 1).

Table 5: Presence of unapproved RMs across selected African countries

African pole	Country	Online evidence of unproven/unlicensed RMs
Western Africa	Nigeria	Yes
Western Africa	Senegal	Yes
Western Africa	Ghana	Yes
Western Africa	Côte d'Ivoire	Yes
Central Africa	Cameroon	Yes
Central Africa	Republic of Congo	Yes
Central Africa	Angola	Yes
Central Africa	Gabon	No
Eastern Africa	Ethiopia	Yes
Eastern Africa	Kenya	Yes
Eastern Africa	Uganda	Yes
Eastern Africa	Rwanda	Yes
Northern Africa	Tunisia	Yes
Northern Africa	Egypt	Yes
Northern Africa	Morocco	Yes
Northern Africa	Algeria	Yes
Southern Africa	Lesotho	Yes
Southern Africa	South Africa	Yes
Southern Africa	Botswana	Yes
Southern Africa	Namibia	Yes

Of the 20 African countries, online websites and clinics through which unapproved RMs are peddled could be found in 16, being present in all the regions/poles. Only Gabon could not be associated with such vendors.

3.3 Regulatory overview of RMs across African countries

Although each of the 20 countries has a National Health Law and/or a Drug regulatory framework, none of these directly engages the range of clinical and regulatory concerns that are unique to RMs. However, four countries have Documents that indirectly engage the issues (Table 6).

Table 6: Presence of RMs regulation across selected African countries

African pole	Country	Direct Mention of RMs in National Drug Laws or Gazettes	Indirect Reference to RMs in National Drug Laws or Gazettes
Western Africa	Nigeria	No	No
Western Africa	Senegal	No	No
Western Africa	Ghana	No	No
Western Africa	Côte d'Ivoire	No	No
Central Africa	Cameroon	No	No
Central Africa	Republic of Congo	No	No
Central Africa	Angola	No	No
Central Africa	Gabon	No	No
Eastern Africa	Ethiopia	No	No
Eastern Africa	Kenya	No	No
Eastern Africa	Uganda	No	Yes
Eastern Africa	Rwanda	No	No
Northern Africa	Tunisia	No	Yes
Northern Africa	Egypt	No	Yes
Northern Africa	Morocco	No	No
Northern Africa	Algeria	No	No
Southern Africa	Lesotho	No	No
Southern Africa	South Africa	No	No
Southern Africa	Botswana	No	Yes
Southern Africa	Namibia	No	No

4. Discussion

This section examines the indirect references made to RMs in the regulatory documents of Uganda, Tunisia, Egypt, and South Africa. On that note, it shows that the undeveloped nature of a proper regulatory/governance structure creates a regulatory vacuum that exposes patients to potential and actual harms.

4.1 Indirect References to RMs in Some Extant African Regulatory Documents

Only the extant regulatory Documents (Laws and/or Gazettes) from 4 of the 20 countries have indirect references and engagement with RMs.

4.1.1 Egypt

Although Egypt lacks a proper regulatory governance for RMs (Sleem, 2012; Mahmoud, 2022), little or no RM regulation in Egypt, though the Egyptian Medical Syndicate allows research only on adult stem cells and prohibits the use or the creation of human embryonic stem cells (Sleem, 2012). Although extant regulatory documents and Ministerial Declarations do not make any reference to RM-related issues; Egyptian clinical scientists have published extensively on different aspects of RMs. They have also been involved in conducting interventional CTs on RM therapies. The regulatory vacuum in Egypt presents potential opportunities for unapproved RM therapies and products to be marketed to vulnerable patients.

4.1.2 South africa

The South African Health Act of 2004 empowers the Minister to regulate the storage, harvesting, utilization or manipulation of tissue, blood, blood products, organs, gametes, oocytes or human stem cells; no specifics have been provided on the processes and guidelines that should inform such regulation. The nature and the extent of that regulation are also not stated in the document (Government Gazette, 2004); neither does it offer a definition of —cells‖ or —stem cells‖, and it is unclear if the notion of —tissue‖ has —cells‖ and —stem cells‖ subsumed in it by proxy (Lawrence, 2017). As such, the South African Act merely offers partial relief to the regulatory vacuum (Pepper, 2012). In addition, the Genetic Modified Organism Act of 1997 applies only to the use of gene therapy (in s.2(1)(c)), but not techniques involving human gene therapy (Viljoen et al., 2022).

South Africa has a pressing need for RM-based therapies to address infectious diseases, as a short-term priority, and lifestyle diseases, as a long-term priority, in South Africa (Jackson & Pepper, 2013). This unmet medical need for cell and gene-based therapies (Pepper, 2012) and the presence of a regulatory vacuum create a scenario where vulnerable patients are exploited by clinics offering unproven therapies (Meissner-Roloff & Pepper, 2013). This state of affairs contributes to the use and sales of unapproved RMs.

4.1.3 Tunisia

A search using keywords related to RM (e.g., stem cells, regenerative, mesenchymal, cord blood, bone marrow, and autologous cells) through the Medicinal Products Registration Guide (Republic of Tunisia, 2016) shows no results for these words. A thematic reading of the document also shows that no provision has been made for RM-related activities. However, the Guide stipulates that medicinal product can be provided for free or against payment without receiving a Marketing Authorization from the Ministry of Health after the Committee consultation. Although Tunisia has a general process for this,

that process was designed to evaluate conventional drugs. In other words, in the event that any RM products that have been licensed elsewhere get imported into Tunisia, it would seem that the Guide offers a general approach to how such products would be evaluated prior to receiving the necessary approval. However, it is hardly possible that Tunisia possesses the expertise to evaluate, pre-clinically and clinically, all types of RM therapies that may be imported. This echoes the need for a specific regulatory framework. The prevailing vacuum, nevertheless, leaves patients who may need RM therapies vulnerable to exploitation and exposure to unsafe and unproven products. A number of online clinics and physician-affiliated outlets actively advertise their —expertise in stem cells therapy, ignoring or bypassing the regulatory prism of the Medicinal Products Registration Guide.

4.1.4 Uganda

Although the recent National Drug Authority (NDA) requires that all pharmaceutical products intended to be marketed in Uganda meet the acceptable standards of quality, safety, as well as efficacy; that such products should be manufactured in facilities that comply with Good Manufacturing Practices, its guidelines are ambiguous vis-a-vis RMs. Specifically, they apply to well-established and well-characterized biotherapeutic products such as recombinant DNA-derived therapeutic proteins, with the exception of vaccines and plasma-derived products and their recombinant analogues (NDA, 2023). This exception becomes problematic considering the fact that (1) not all DNA-derived therapeutic proteins may be classified as gene therapies, and consequently, will be eligible for classification as RMs. Teasing out the necessary distinctions is, therefore, fuzzy as far as the prescription of the NDA goes. (2) Several products including stem cells, platelet-rich plasma, and white cells are, technically, all plasma-derived products. Since some of these are already a part of mainstream clinical practice either in whole blood transfusion or targeted transfusion in Uganda, (George et al., 2022) the exception clause becomes ambiguous.

Against this backdrop, it may be inferred that the RM regulatory landscape in Uganda is vacuous when the extant regulatory instruments are considered. A second but equally valid inference is that there exists some ambiguity in relation to specific classes of what may fall into the category of RMs. A significant consequence of this state of affairs is the exploitation of patients who may be seeking RMs for their medical conditions. Not surprisingly, some online channels are already taking advantage of this situation.

Regardless of the benefits that some patients may derive from such avenues, the uncertainties (e.g., risk-benefits ratio, side effects, and long-term complications), that characterizes such and other clandestine RM therapies underscore the urgent need to develop a regulatory framework.

The discussion above clearly shows that a regulatory vacuum for regenerative medicine therapies and products exists in all these four African countries, though the extant literature indicate South Africa as having the highest incidence of unapproved RMs (Mahomed, S., & Slabbert, 2012; Horn, 2015). However, the medical and genetic conditions as well as chronic diseases (e.g., hemophilia, sickle cell disease, diabetes mellitus, and infertility) that lead patients to seek such therapies or for local physicians and scientists to offer such treatments are not exclusively restricted to these countries but exist across different parts of Africa.

4.2 The harms of unapproved and unlicensed RMs

A number of positive clinical outcomes have been associated with some RM treatments, even in African patients. For instance:

In December 2012, Kyle and Carla Poppleton were expecting their first child. The couple, who lived in Botswana, decided to collect their new baby's cord blood and tissue cells to take advantage of the new advanced form of medicine, stem cell therapy, and safeguard their new child's health.² In March 2013, the Poppletons welcomed their daughter Paige into the world.³ Within just a year Paige was diagnosed with cerebral palsy, and by the next six months she could not sit up and kept her right hand in a fist shape most of the time. In April 2014, Paige's umbilical cord blood stem cells were transferred to Duke University in North Carolina, where the cells were transplanted and reinfused into Paige's body. Two months after the infusion Paige began crawling, pulling herself to stand up, and holding her parents hands once again (Kossow, 2022)

However, the regulatory vacuum for RMs across African countries exposes them to unapproved and unlicensed RMs, which pose different kinds of harms to patients across the globe. Unethical attempts to use stem cell therapy in the treatment of renal failure can be found in several countries around the world including African countries (Wiwanitkit, 2019). Medical tourism previously served as the route through which patients in Africa could access such treatment. The travel destinations were facilities located in countries such as China, India, and Russia, where a lack of rigorous regulatory oversight allow providers of clinics to operate (Murray et al., 2020). Although the travel-mediated RM treatment still occurs, unproven RM therapies are increasingly being offered directly to patients via online channels, or through local —experts‖ in African countries (See Appendix 1). Generally, the harms associated with RMs may be medical, psychological or financial.

4.2.1 Medical harm of RMs

Patients who receive unapproved RMs face significant medical harms. For instance, several Ghanaian patients with ocular diseases have been seriously and permanently injured by unapproved stem cell therapies (Margolis, 2022).

Indeed, receiving unapproved RMs has led to incidents of bilateral loss of vision in some patients (Murray *et al.*, 2020). In the case of an Egyptian patient with acute transverse myelitis was treated with unapproved mesenchymal stem cells (MSCs), the treatment provoked an autoimmune reaction, which resulted to acute disseminated encephalomyelitis (Bauer *et al.*, 2018).

A study of 180 patients who received allogeneic hematopoietic stem cell transplantation reported different incidence rates of bronchiolitis obliterans based on the genetic profiles of the patient population (Touihri *et al.*, 2019). Antibiotic resistance has also been identified as a cause of concern in Tunisian recipients who receive hematopoietic stem cell transplants (Mechergui *et al.*, 2019). Some patients have also suffered paraplegia after receiving unapproved RMs (Murray *et al.*, 2020). These observations reinforce the need for a proper regulatory framework to shape and inform the different pre-clinical and clinical research processes that underpin RMs in order to ensure that only safe products and therapies are available to patients across Africa. However, the under-reported nature of such incidents (Bauer *et al.*, 2018) and the fact that such incidents have only begun to receive attention show that the true level of harms associated with the use of unproven and unlicensed RMs in Africa is not known.

4.2.2 Psychological & financial harms of RMs

Although conventional treatments may sometimes lead to poor clinical outcomes, such cases are often the exception. However, patients who receive unapproved and unlicensed RM therapies that fail to work for the acclaimed disease condition or that lead to adverse physical harms may suffer additional psychological and financial harms (Zatz, 2009; Bingen & Hoag, 2016). For instance, the disappointments of treatment failure as well as the accompanying financial loss (through spending thousands of foreign currencies) may lead to depression in some patients, thereby further impairing their quality of lives.

On the one hand, these three-fold kinds of harms associated with unapproved and unlicensed RMs underscore the need for serious vigilance over the clandestine marketing, sale and use of approved RMs in Africa. On the other hand, the situation highlights the need to develop a proper regulatory framework for RMs.

5. Developing an innovative regulatory framework for RMs in Africa

Drugs and therapies that fall within the genre of regenerative medicines are usually alive, and can be perceived as having more in common with transfusions (e.g., of blood, of tissues, or organs) than with conventional medicines and medications that are typically dispensed by pharmacists (Jordaan, 2012). Therefore, the first step in the development of a distinct regulatory framework for RMs for African countries is the recognition of the

specific distinctions between existing therapies/drugs and RMs (e.g., modified cells and genes, cell therapies, and tissue-engineered products).

The ethical imperative for regulating RMs in Africa springs from the duty of nations and their regulatory bodies to protect the public health. Since the goal of regulatory mechanisms of RMs is lessening the potential harms of unproven stem cell treatments while still maintaining patient access to proven therapies (Kossow, 2022), then it is important for countries in Africa to develop national frameworks to curb the multi-faceted harms that unproven RMs pose to their citizens.

5.1 Stakeholders' approach to developing RMs regulation

Because every society have multiple stakeholders with distinct sets of values (ideological, secular, and religious), stakeholders in each African country must see the need to preven the harms associated with the practice of unapproved RMs, debate the relevant issues, and develop actionable policies. Some of the specific stakeholders and their possible roles include:

5.1.1 Drug regulatory bodies

Most African countries have extant Drug regulatory policies that specific the rigorous processes that pharmaceutical drugs and products must pass through from the pre-clinical to the clinical and marketing stages of development. The previous experience gained ffrm their regulatory functions will be integral to developing the specific protocols that RMs need to g through in the African context.

5.1.2 University scientists/clinicians

Universities play important roles in innovation systems (Lundvall, 2007), Several African universities have researchers and clinicians who have a keen interest in regenerative medicine research, as evidenced by publications in peer-review journals. By fiat of this close association with the field, they can examine the regulatory policies in countries (e.g., USA, Canada, Japan, Turkey, and South Korea) that have developed them and utilize their expertise in coming up actionable policies that will speak to their local realities.

5.1.3 Patients

Patients who have previously used unapproved RMs and those seeking conserving them should be identified and their unique experiences and perspectives tapped into. This will be in order to incorporate relevant insights into the RM policies.

5.1.4 The general public

Although RMs have enormous potentials in the treatment of acute and chronic genetic, metabolic, and degenerative disorders (Yamanaka, 2020; Melton, 2021), they sometimes raise ethical issues. Since the delivery of healthcare services and products occurs within a social context (Pellegrino & Thomasma, 2004), whether or not embryonic stem cells should be used and the extent of applications (e.g., somatic versus reproductive uses) are some of the concerns and issues that the general public will need to be involved in vis-à-vis transparent public discourses.

6 Conclusion

The regenerative medicine therapy regulatory landscapes in the selected African countries examined in this paper are generally characterized by the absence of governance structures that address the processes necessary for the evaluation and approval of RMs. The regulatory vacuum has contributed to making some patients in these countries targets of unproven cell and gene therapies. The several harms associated with such therapies, however, places ethical burdens on these countries to develop viable policies to protect the public health of their citizens. In this regard, a stakeholders approach involving university-based researchers, existing drug regulatory agencies, patients, and the general public will be key to how each African nation will develop an innovative RM policy that reflects her unique values, needs, and preferences.

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Appendix 1: Weblinks to Unproven RM Therapies across Selected African Countries

Region/Pole	Country	Online RM vendors or clinics	Weblinks of such RM vendors/clinics
Western Africa	Nigeria	Yes	https://www.cystemcellcenter.com/stem-cell-treatment-in-nigeria/ https://glorywellnessng.com/ https://netherapy.business.site/?utm_source=gnb&utm_medium=referral https://thegreyness.com/ https://hscellclinic.com/
Western Africa	Senegal	Yes	https://meditourpro.com/stem-cell-therapy-in-senegal/
Western Africa	Ghana	Yes	https://www.c4hr.net/ https://www.myamericansjourney.com/
Western Africa	Côte d'Ivoire	Yes	Several clinics available but no website was found
Central Africa	Cameroon	Yes	https://www.stemcelltherapyindia.com/stem-cell-treatment-for-cameroon-patients.html https://regenespine.com/regenerative-spine-joint-stem-cell-pro-treatment-cameroon-cm/ https://www.vaidam.com/knowledge-center/patient-testimonials/mother-travels-cameroon-stem-cell-procedure-finds-ideal-treatment-her-child
Central Africa	Republic of Congo	Yes	https://www.stemcelltherapyindia.com/stem-cell-treatment-for-congo-patients.html https://www.vieroc.com/
Central Africa	Angola	Yes	https://web.facebook.com/SALIMOR_CONSULTORIO_MEDICO/
Central Africa	Gabon	None	
Southern Africa	Lesotho	Yes	https://www.indoamericanhealth.com/stem-cell-treatment-in-lesotho.html
Southern Africa	South Africa	Yes	https://sastemcells.co.za/ https://www.stemorechute.co.za/ https://capetownstemcellcentre.co.za/
Southern Africa	Botswana	Yes	Several clinics available but no website was found
Southern Africa	Namibia	Yes	https://www.stemcellnamibia.com/
Northern Africa	Tunisia	Yes	https://www.lythait.com/hospitals/stem-cell-therapy-hospitals-and-costs-in-tunisia/
Northern Africa	Egypt	Yes	https://www.vaidam.com/hospitals/orthopedics/orthopedic-stem-cell-treatment/egypt https://r3stemcell.com/egypt/
Northern Africa	Morocco	Yes	https://www.stemcellsgroup.com/global-stem-cells-group-opens-new-medical-office-casablanca-morocco/ https://www.mymeditravel.com/stem-cell-therapy-procedures-in-morocco
Northern Africa	Algeria	Yes	Several clinics available but no website was found
Eastern Africa	Ethiopia	Yes	https://www.placidway.com/profile/2013/PlacidWay-Ethiopia https://www.globalstemcellcare.com/ethiopia/ https://www.mespol.com/ethiopia/all/stem-cell-therapy/all/doctors https://vitalityfountainclinic.com/wound-care/stem-cells-in-kenya/ https://www.the-star.co.ke/health/2020-09-07-stem-cell-therapy-now-available-in-kenya/
Eastern Africa	Kenya	Yes	
Eastern Africa	Uganda	Yes	https://aifetoliveknow.business.site/?utm_source=unib&utm_medium=cferral https://stem-cell-therapy-mitra-cell.business.site/ https://www.agnutritioninternational.com/
Eastern Africa	Rwanda	Yes	https://www.avocure.com/hospitals/medihent-hospital-kigali-rwanda?locale=en&procedure_name=Cancer https://regenespine.com/regenerative-spine-joint-stem-cell-pro-treatment-rwanda-rw/

Economic analysis of indirect groundwater recharge scheme using recycled water in a semi-arid region

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1. Introduction

Water stress characterized both by the scarcity of freshwater resources and the degradation of water quality among freshwater bodies has become an increasingly global concern (Tzanakakis et al., 2020; Lele, 2022). Therefore, in India, as well as many other countries, the reuse of treated wastewater has emerged as an alternative and sustainable water resource for mitigating water stress (Icekson-Tal et al., 2003; Tortajada and Bindal, 2020). Reuse of treated wastewater has multidimensional benefits such as solving wastewater management issues, increasing water supply, recharging groundwater (GW), improving agricultural production, encouraging a circular economy, and protecting natural resources through reducing pollution by decreasing the amount of wastewater discharged into the environment (Guerra-Rodríguez et al., 2020; Ofori et al., 2021; Verma et al., 2023). It is important to note that any wastewater reuse project must adhere to various requirements, including environmental and public health safety, socio-cultural acceptance, and economic considerations (Breitenmoser et al., 2022). Consequently, economic feasibility studies, among others, play a crucial role in assessing the socio-economic, developmental, and sustainability-driven viability of treated wastewater reuse projects while also facilitating and enabling the decision-making process for their promotion and implementation (Fan et al., 2015; Arborea et al., 2017; Bassi et al., 2022;). However, there is a limited number of studies on evaluating the economic feasibility of wastewater reuse projects through cost-benefit analysis primarily in developing countries with a sustainable development focus (Al-Jayyousi, 2003; Karkar et al., 2015; Hanjra et al., 2015; Bassi et al., 2022). Water reuse projects are often overlooked and undervalued when compared to other projects due to a lack of comprehensive evaluation of their tangible and intangible benefits, including social and environmental benefits (Senante et al., 2010; Goyal & Kumar, 2021; Bassi et al.,

2022). Many studies have highlighted the advantages and limitations of wastewater reuse by adopting different end-uses such as irrigation, GW recharge, and non-potable uses but often have not provided proper economic quantification of these benefits (Jaramillo et al., 2017; Aleisa, 2019; Ofori et al., 2021; Nandan et al., 2021). As a result, the total benefits and costs of many projects are inadequately assessed.

Cost-Benefit Analysis (CBA) is an essential tool used by policymakers to evaluate whether a project is worth investing in, by weighing its costs against its benefits (Van der Bruggen et al., 2009; Boardman et al., 2017). In the field of wastewater reuse, CBA can play a pivotal role in the implementation of efficient and effective policies and strategies for wastewater management for ensuring long-term economic, environmental, and social sustainability (Senante et al., 2011; Verlicchi et al., 2012; Fan et al., 2015; Al-Sa'ed et al., 2015; Arborea et al., 2017). In wastewater treatment and reuse projects, costs refer to the expenses associated with the design, construction, operation, and maintenance (O&M) of the treatment facility and water pumping. O&M costs may include the cost of purchasing equipment and chemicals, electricity, labor, and other utilities. On the other hand, benefits refer to the conservation of water resources, protection of the environment as well as nearby freshwater bodies, sustaining safe water sources, enhancement of irrigated land area and avoiding land alienation, improved agricultural production, farm-family incomes, socio-economic status, water security to agriculture and rural life, reduced pressure on outmigration and improved public health (Ortiz et al., 2007; Kumar & Tortajada, 2020).

Several studies have carried out CBA of treated wastewater reuse projects, evaluating the benefits of such systems from different perspectives. For instance, Godfrey et al. (2009) analyzed the economic and health benefits of treated greywater reuse in a residential school of Madhya Pradesh, India. Fan et al. (2015) focused on the tangible benefits of reclaimed wastewater reuse in Beijing, including revenues from selling the reclaimed water, savings from substituting public water supplies with reclaimed water, and reductions in fertilizer use when reclaimed water is used in crop and landscape irrigation. Senante et al. (2010) conducted a CBA analysis of wastewater treatment in which they evaluated the environmental benefits by calculating the shadow prices of undesirable outputs produced in the treatment process and found that nutrient removal provided the maximum environmental benefits. A similar study was conducted by Arborea et al. (2017) and Arena et al. (2020) in Puglia, Southern Italy where the benefit was evaluated on economic value of direct use of reclaimed water for irrigation and improvement in GW quality. While a few other studies have concentrated on analyzing the economic advantages of irrigation in agriculture and the potential for recovering nutrients from wastewater to improve the environment (Lienhoop et al., 2015; Huang et al., 2020; Canaj et al., 2021; Četković et al., 2022; Nepfumbada et al., 2023; Li et al.,

2023). Senante et al., (2011) presented a methodology that considers internal and external impacts to assess the economic feasibility of phosphorus recovery from wastewater, including estimating the shadow price of phosphorus using the directional distance function, and concluded that phosphorus recovery is not only beneficial for sustainability but also economically viable when environmental benefits are considered. Beckinghausen et al. (2020) compared different nitrogen recovery technique and their energy requirement from wastewater, finding gas-permeable membrane technology as a potential low-energy solution and suggested that further research is needed for techniques like vacuum membrane distillation. Shadow costing of avoided environmental damage reversal as well as direct benefits accrued from recovery or reuse of nutrients are key approaches, although added water security and risk reduction have not been accounted for from a socio-economic perspective in a large number of cases.

Goffi et al. (2018) revealed that the most critical economic factors for establishing and selecting wastewater treatment (WWT) systems are investment costs, energy requirements for running them, skill levels for operation, O&M, and land requirements, whereas other factors, including environmental, technical, and social criteria considered with a lower priority. These findings are particularly relevant for developing countries like India, which are seeking for economically viable WWT solutions (Goffi et al. 2018; Bassi et al., 2022) which are also sustainable and inclusive.

In developing countries, there is often a significant gap between the volume of wastewater generated in urban areas and the capacity to treat it. Further, the limited financial and human resources, regulatory compliance, and lack of economic feasibility make it challenging to implement wastewater treatment and reuse schemes (Robbins et al., 2022). Therefore, CBA can be a crucial tool for decision-makers in promoting the reuse of wastewater in these contexts. A review of CBA published literature reveals that, in India, there are currently only a few projects focused on the wastewater recycling and reuse and there were major gaps in the economic viability of these projects (Bassi et al., 2022). A large-scale wastewater recycling project known as Koramangala & Challaghatta valley (K&C valley) was initiated by Govt. of Karnataka, India which aims for indirect GW recharge using secondary treated water (STW) coming from Bangaluru, India to fill surface tanks (irrigation tanks) of the neighboring semi- arid and drought prone districts of Kolar and Chikkaballapur located to the North and East of the city of Bangaluru (Singh, 2020; Verma et al., 2023). Around 440 MLD of treated wastewater is currently pumped and later distributed by gravity to over 137 irrigation tanks which in turn recharge the GW in the nearby villages. The project is one of the largest of its kind in India and is unique in several ways such as it addresses the issue of continued serious water scarcity in the region, improving GW quantity and quality, agricultural productivity, and socio-economic status (Verma et al.,

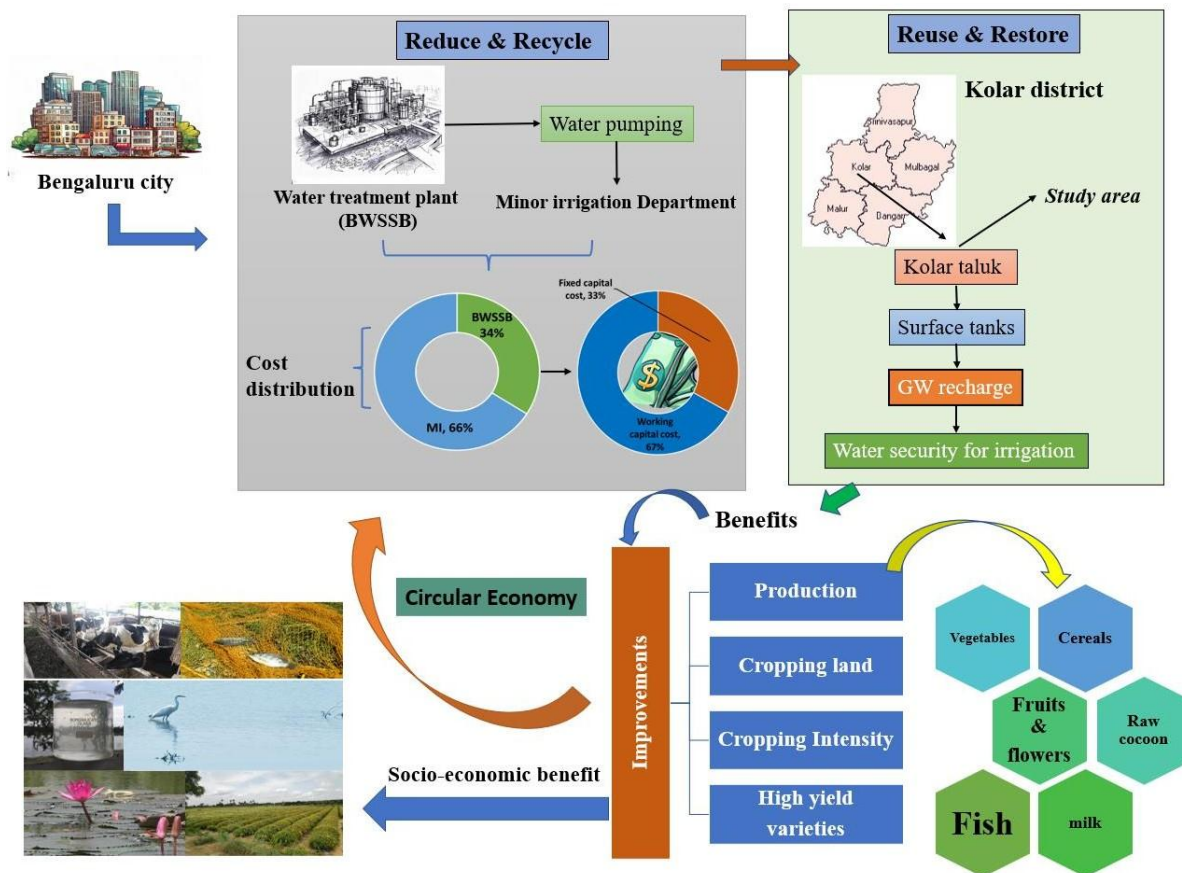
2023). Its success has led to such wastewater recycling models being emulated across other metro-cities of India. Even though the success of the K&C Valley project is visible on the ground there is a lack of effort in quantifying the significant benefits that have been accrued to various stakeholders of the project. A comprehensive cost- benefit assessment of the K&C Valley project, if made available, would be of great help to governments, urban planners and institutions, and policymakers for decision making, implementation, and scale-up with respect to such projects. Thus, the objectives of this study are – (i) to quantify the investment and operational costs incurred by the relevant government institutions in the implementation of a water recycling project, (ii) to quantify the benefits accrued to various stakeholders by accounting revenue generated from improved agricultural productivity and resultant sales of produce of agricultural, horticultural, sericultural (raw cocoon), milk and fish catch based activities in the area (iii) to perform the detailed CBA of such a unique system. In this study CBA was done using conventional methodologies of economic analysis including “Net present value (NPV)” and “Benefit-cost ratio (BCR)” (Seguí., 2004; Van der Bruggen et al., 2009; Hernández et al., 2010; Senante et al., 2011; Verlicchi et al., 2012).

2. Methodology

2.1 Study area

The K&C Valley indirect GW recharge project is unique in its outcomes and is a joint initiative undertaken by the Minor Irrigation Department (MI), the Government of Karnataka, and the Bangalore Water Supply and Sewerage Board (BWSSB) in March 2018 to address the prolonged and acute drought situation of semi-arid Kolar district, Karnataka. The project involves the rejuvenation of a series of existing man-made surface tank cascades and filling them with recycled water coming from Bengaluru, urban areas, and directing it into the GW aquifers through soil strata infiltration. This project encompasses five Taluks (sub-unit of a district), namely Kolar, Srinivasapura, Mulabagilu, Bangarapet, and Malur of the Kolar district (**Fig.1**). It has already shown promising outcomes in terms of recharged GW table, improved GW quality, and other socio-economic benefits (Singh et al., 2020; Verma et al., 2023). This study, however, is restricted to only Kolar Taluka with the following features: geographical area – 69,210 hectares (ha), cultivated area – 35,715 ha, surface tank -42, total population- 3,85,410 (rural population-2,46,948 and urban population-1,3,8,462), and major occupation- agriculture and associated activities. As part of the recycling project in Kolar Taluk, 146 MLD of treated wastewater is pumped into a 42 surface tanks. **Fig. 1** illustrates the contribution of the K&C valley projects towards the circular economy by implementing the 4'R framework, namely reduce, recycle, reuse, and restore (Morseletto et al., 2022). These initiatives aim to promote sustainable development in the water sector while enhancing the socio-economic status of the local community.

Fig. 1 Conceptual framework: contribution of the K&C valley projects towards the circular economy and socio-economic development



2.2 Data collection

2.2.1 Wastewater recycling cost

The K&C Valley recycling project is split into two components, with the BWSSB responsible for establishing the sewage treatment plant (STP) using secondary wastewater treatment technologies to treat the municipal wastewater. However, MI department has played a crucial role in the project by conceptualizing and designing the recycling project, installation of a pumping station, electrical substation, diesel generator set (4000 KV), and the construction and renovation of a canal to pump water into different surface tanks in Kolar and Chikkaballapur districts. Therefore, cost data related to the water treatment process was obtained from both the BWSSB and the MI department (**Fig. 2**). This data was obtained from the concerned officers of the BWSSB and MI departments, who have been overseeing the project's implementation.

2.2.2 Benefits

The implementation of the recycling project has been considered to have a positive impact on the GW table in the area (Verma et al., 2023). As a result, the borewells have been rejuvenated, allowing for increased access to water in a drought prone district. This increase in water availability generated significant benefits for the local community, particularly in terms of an increase in agricultural production and socio-economic status (Verma et al., 2023). Therefore, data related to the agricultural area and productivity, sericulture (raw cocoon), fish and milk production along with the yearly average rate of produce was obtained by reaching out to different government organizations of Kolar district such as the departments of agriculture, horticulture, sericulture, fisheries, Kolar-Chikkaballpura district co-operative milk producers union Ltd. (KOMUL), etc. Data was collected from these organizations for the Kolar Taluka for a period of nine years, ranging from 2014 to 2022. The data collected was categorized into two groups: 'before-recycling' data for the years 2014-2018, and 'after-recycling' for the years 2019-2022. However, it should be noted that the study focuses on key sectors indicated above, while other associated benefits in sectors such as employment generation, reverse ruralization, and biodiversity improvement will be dealt with elsewhere primarily due to the paucity of validated data and methodological constraints.

2.3 Data analysis

2.3.1 Cost benefit analysis (CBA)

The present CBA involves assessing the economic feasibility of a project by comparing its total costs to its total benefits, which are also measured in monetary terms. The CBA involves evaluating several key indicators beginning with NPV (Verlicchi, et al. 2012). NPV is a metric used to measure the economic value of the project by calculating the difference between the total discounted benefits and the total discounted costs. In simpler terms, NPV takes into account the time value of money by adjusting for inflation and discounting future cash flows and provides a way to estimate whether the project will generate positive or negative returns over its lifetime. In the present study NPV calculation presented in Eq. (1), where TC and TB are, respectively, the total cost and benefit in the year t , r is the discount rate, and T is the expected plant lifespan. The cash flows for the project have been projected over a period of 25 years, which is deemed to be an appropriate time horizon based on the project's estimated useful life. This time frame allows for a comprehensive assessment of the project's financial performance, taking into account both short-term and long-term costs and benefits. By analyzing cash flows over a 25-year period, decision-makers can more accurately evaluate the project's economic viability and determine whether it aligns with their investment objectives.

$$NPV = \sum_{t=0}^T TB(1+r)^{-t} - \sum_{t=0}^T TC(1+r)^{-t} \dots\dots\dots (1)$$

If the $NPV \geq 0$ the project investment is said to be beneficial since the benefits outweigh its investment. Another useful indicator in CBA is benefit-cost ratio (BCR). It is the ratio of the total present value of benefits and the total present value of costs, presented in Eq. (2), where TC and TB are, respectively, the total cost and benefit in the year t, r is the discount rate, and T is the expected plant lifespan.

$$BCR = \frac{\sum_{t=0}^T TB(1+r)^{-t}}{\sum_{t=0}^T TC(1+r)^{-t}} \dots\dots\dots (2)$$

If $BCR > 1$, the project is considered as economically feasible.

NPV is generally used when the objective is to maximize the total value of the project, while BCR is preferred when the objective is to compare the relative benefits and costs of different projects.

The stakeholders of "cost" in this study are the government, while the stakeholders of "benefits" are farmers. Although the government may incur short-term costs to implement policies that benefit farmers, such investments can have long-term benefits for society, including increased food security, improved nutrition, and reduced poverty. Furthermore, investing in agriculture can stimulate economic growth in rural areas, create job opportunities, and lead to the development of related industries, such as manufacturing and transportation.

2.3.2 Cost analysis

In the present study, the annualized total costs (ATC3) for the project were calculated by combining annualized total cost of wastewater treatment (ATC1) and water pumping (ATC2), as presented in **Table 1**. The costs of wastewater treatment, which were incurred by the BWSSB, include the fixed capital cost (FCC1) for constructing the STP. This includes the costs of civil works (A1) and electrical and mechanical works (E&M) (B1). In addition, the working capital cost (WCC1) was considered, which includes the annual O&M costs. These O&M costs include expenses for power (C1), civil repairs (D1), engineering and maintenance (Engg. & M) (E1), chemicals (F1), and manpower (G1). Similarly, the costs of water pumping, which were incurred by the MI department, were also calculated. This includes the fixed capital cost (FCC2) and working capital investment (WCC2). However, FCC was calculated based on a @5% and @8% interest rates (I) for 25 years. The ATC3 was calculated as given in following Eq:

$$ATC_3 = ATC_1 + ATC_2 \dots\dots\dots (3)$$

$$ATC_1 = A_1 + B_1 + C_1 + D_1 + E_1 + F_1 + G_1 \dots\dots\dots (4)$$

$$ATC_2 = A_2 + B_2 + C_2 + D_2 + E_2 + F_2 + G_2 \dots\dots\dots (5)$$

$$\text{So, } ATC_3 = A_3 + B_3 + C_3 + D_3 + E_3 + F_3 + G_3 \dots\dots\dots (3)$$

$$\text{Where, } A_3 = A_1 + A_2; B_3 = B_1 + B_2; C_3 = C_1 + C_2; D_3 = D_1 + D_2; E_3 = E_1 + E_2; F_3 = F_1 + F_2; G_3 = G_1 + G_2$$

Note: A=civil work, B=E&M work, C=power, D=civil repair, E= Engg.&M, F= chemicals, G=manpower, 1= water treatment cost, 2= water pumping cost, 3= total cost (1+2)

2.3.3 Benefit analysis

The present study focused on analyzing the economic benefits of four main factors. Firstly, the study has examined the benefits accrued in agriculture and horticulture production due to assured and improved water availability for irrigation from the shallow GW table, even during droughts (water security for agriculture). Secondly, the study examined the improvement in raw cocoon production under sericulture due to improved water availability and mulberry production around the year and concomitant potential to raise silkworms for many more cycles in a year. Thirdly, the study explored the improvement in milk production resulting from an increase in cattle rearing due to the increased availability of green fodder. Fourth, the study investigated the positive impact on fish production due to year-round water availability in tanks leading to longer growth periods for fish rearing as well as a higher water storage volume in tanks leading to higher fish stocking densities. To estimate the economic benefits of the project, revenue generated from the sale of the produce from (i) agricultural and horticultural, (ii) sericulture (raw cocoon), (iii) milk, and (iv) fish rearing activities were aggregated.

The agricultural crop production data analyzed in this study included three primary types, namely agricultural crops (cereals and pulses), horticultural crops (predominantly vegetables and fruits), and floricultural crops (flowers generally raised for export and domestic uses). This type of grouping was a necessity arising from the way in which data is being collected and managed by these governmental departments. For the purposes of benefit analysis, two of the highest grown and/or traded crop types were selected from each of these groups. These present the dominantly cultivated crop types as well as by area cropped. This approach ensured that the analysis provided insights that were valid, relevant, and useful for farmers and policymakers in the overall agricultural sector. **Table 3** presents the estimation of the benefits in terms of the total average gross revenue (AGR) generated from different sectors. However, the total agricultural production was calculated based on the data obtained for the total agricultural crop area and productivity. Therefore, to determine the total AGR for agriculture (W), sericulture (raw cocoon) (X), milk

(Y), and fish (Z) production, the approach is presented in Eq. 6,7,8, 9 respectively (**Table 3**).

$$W_3 = W_1 * W_2 \dots\dots\dots (6)$$

$$X_3 = X_1 * X_2 \dots\dots\dots (7)$$

$$Y_3 = Y_1 * Y_2 \dots\dots\dots (8)$$

$$Z_3 = Z_1 * Z_2 \dots\dots\dots (9)$$

The focus of this study was to analyze the benefits derived from the implementation of a recycling project. In order to determine the overall economic benefit, a linear extrapolation was conducted on the total production data, using the year 2018 as a reference point to establish a business-as-usual case (Mühlbach et al., 1987; Liu, 2006). Subsequently, the total benefit (TB) for each sector was calculated by taking the difference between the total AGR and the estimated revenue from the business-as-usual scenario. Finally, the calculation of the TB resulting from the recycling project for each sector was carried out using Eq. (10).

$$TB_5 = TB_3 - TB_4 \dots\dots\dots (10)$$

$$\text{Where, } TB_3 = W_3 + X_3 + Y_3 + Z_3$$

$$TB_4 = W_4 + X_4 + Y_4 + Z_4$$

Or,

$$TB_5 = W_5 + X_5 + Y_5 + Z_5 \dots\dots\dots (10)$$

Where, $W_5 = W_3 - W_4$; $X_5 = X_3 - X_4$; $Y_5 = Y_3 - Y_4$; $Z_5 = Z_3 - Z_4$

Note: W=agriculture and horticulture; X= raw cocoon, Y=milk, Z= fish; 1=production;

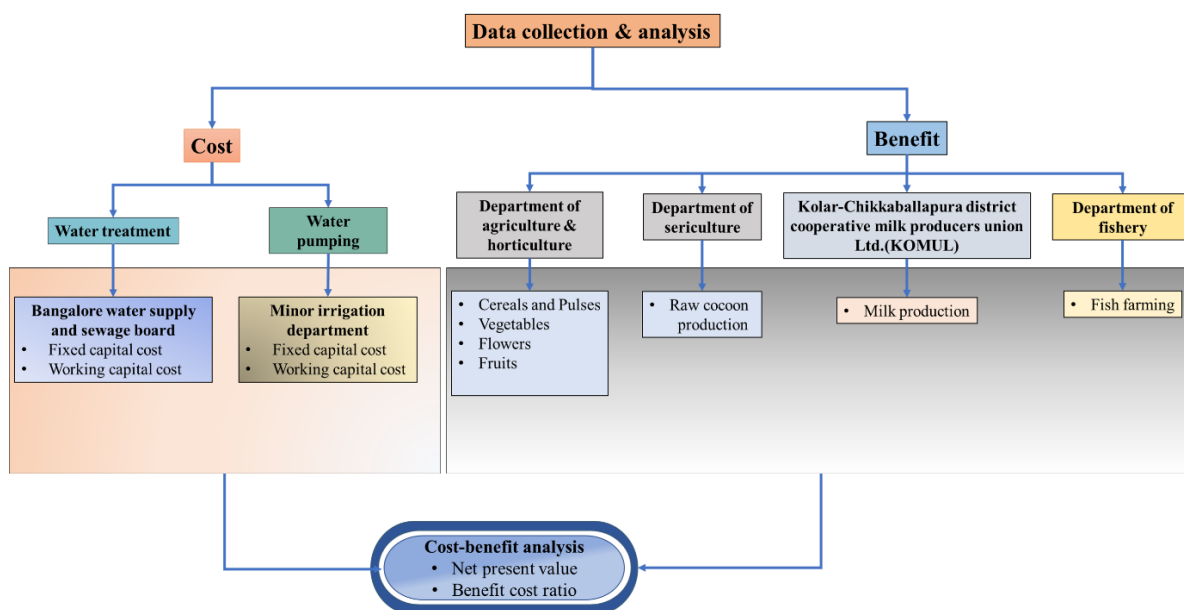
2=market rate; 3= average gross revenue; 4=business as usual; 5= total benefit (4-3)

To evaluate the economic feasibility of the project over a 25-year period, the values obtained were used to forecast both the reported revenue and the business-as-usual case revenue. Later the future values were converted in to present values by applying discounting factor of 5%. A schematic diagram of the methodology including data collection and analysis has been presented in **Fig. 2**.

This approach allowed two perspectives, one from an investment perspective wherein, the metropolitan city (or any urban local body) is expected to treat its municipal wastewater to a certain level of treatment and release it to the nearest water body. This was the scenario because the access to fresh water was high, and it could be procured at relatively low costs. In this scenario, the water for filling surface tanks in Kolar district is obtained at 'zero' cash cost to the system that only needs to carry out all post-treatment activities. Also, there is no entitlement to this water and hence has 'zero' opportunity costs saving the costs of 'disposal' of a city. The second scenario is likely to describe a water-

constrained climate-influenced scenario, wherein the treated water, after-treatment is considered to have some kind of entitlement, the treatment to the required level is an opportunity for doing business and finally, there is also the cost to pump it, and distribute it to the surface tank far away. Therefore, this water suffers both treatment and distribution costs and by virtue of the opportunity to sell it, it is expected to market it at prices that are inclusive of the overall costs. The costs of water thus supplied are of two types and are discussed in the results section.

Fig 2. Schematic diagram of the methodology



3. Results and discussion

3.1 Cost of the recycling project

Table 1 shows the annualized total cost (ATC₃) of the recycling project was ₹4.53 million/MLD @5% interest rates on the FCC. This cost includes both the cost of water treatment, which was ₹1.55 million, and the cost of water pumping, which was ₹2.98 million. However, @8% interest rates on the FCC, the ATC₃ amounted to ₹5.33 million /MLD. The total cost of per 1000 litres (KL) recycling project was ₹12.43 @5% and ₹14.61@8% interest rates. Based on the cost analysis, the annualized total cost of the pumping 146 MLD of treated to Kolar Taluk's 42 surface tanks was estimated to be ₹661 million @5% and ₹778 million @8% interest rates.

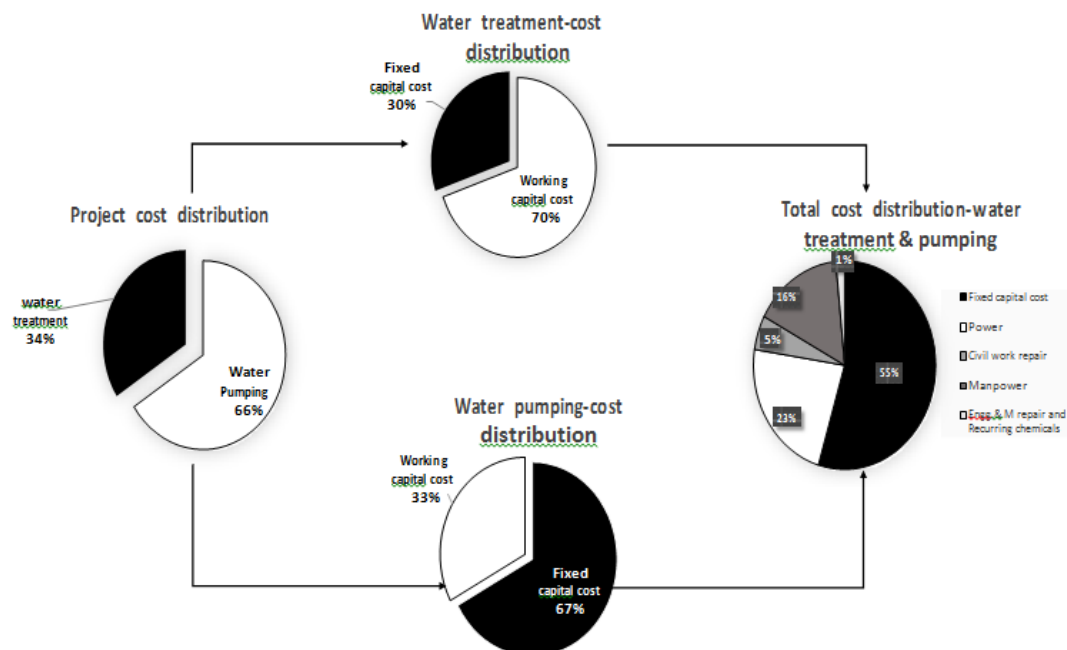
Upon further analysis, it was observed that the majority of the investment was covered by the MI department for water pumping, which accounted for 66% of the total cost. For water treatment, 30% of the cost was attributed to FCC, which was ₹0.47 million, while the majority of the cost was allocated to WCC. However, for water pumping, 67% of the cost was related to FCC, and 33% was for WCC. Power cost was found to contribute the most, accounting for 50% of the TC3 of WCC. The high-power cost is mainly due to the energy demands required for operating the water treatment and water pumping stations. **Fig. 3** presents the distribution of costs in different categories.

Table 1. Cost of the recycling project

Category	Costs	BWSSB- Annualised water treatment cost/MLD [1]		MI - Annualised water pumping cost/MLD [2]		Total cost (TC)/MLD [3] = (1+2)	
		Million Rupees @5% I [i]	Million Rupees @8% I [j]	Million Rupees @5% I [i]	Million Rupees @8% I [j]	Million Rupees @5% I [i]	Million Rupees @8% I [j]
A	Civil works	0.29	0.37	0.86	1.14	1.15	1.51
B	E&M works	0.18	0.25	1.14	1.51	1.33	1.76
Fixed capital Cost(FCC) (A+B)	Capital cost	0.47	0.62	2.00	2.65	2.47	3.27
C	Power	0.39	0.39	0.64	0.64	1.03	1.03
D	Civil work repair	0.12	0.12	0.12	0.12	0.24	0.24
E	Engg. &M repair	0.04	0.04			0.03	0.03
F	Recurring chemicals	0.04	0.04	0	0	0.04	0.04
G	Manpower	0.49	0.49	0.22	0.22	0.71	0.71
Working capital cost (WCC) (C+D+E+F +G)	Total operation and maintena nce cost	1.08	1.08	0.98	0.98	2.06	2.06
Annualised total cost (ATC) /MLD (FCC+WCC)		1.55	1.70	2.98	3.63	4.53	5.33
Cost of KL		₹4.25 \$0.051	₹4.66 \$0.056	₹8.18 \$0.10	₹9.95 \$0.12	₹12.43 \$0.16	₹14.61 \$0.17

Source: Authors' estimates-based on data from BWSSB and MI department

Fig 3. Cost distribution of recycling project @5% interest rates on FCC



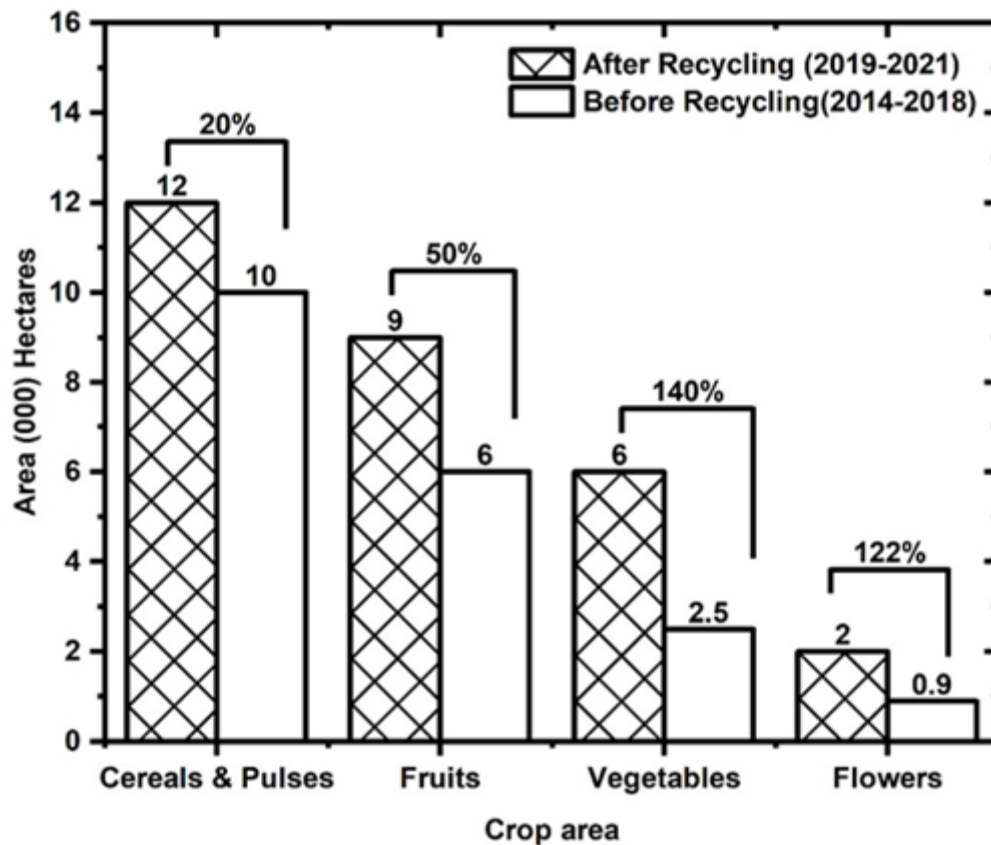
3.2 Benefits of recycling project to stakeholders

3.2.1 Increase in cultivated agricultural land

The data presented in **Fig. 4** highlights a significant increase in the average crop area cultivated by farmers during the after-recycling period compared to the before-recycling period. The increase was observed across all crop categories, with the highest increase observed in vegetables, followed by flowers and fruits. The cultivation of vegetables showed the most significant increase of 140%, from 2.5 thousand (Th) ha to 6 Th ha. The cultivation of flowers increased by 122%, from 0.9 Th ha to 2 Th ha, while the cultivation of fruits increased by 50%, from 6 Th ha to 9 Th ha. In contrast, the cultivation of cereals and pulses showed a comparatively modest increase of only 20%, from 10 Th ha to 12 Th ha. Firstly, it appears that a lot of land is maintained fallow for want of water for protective or intensive irrigation. Second, this increase in crop area can be explained by the availability of assured water throughout the year, which allowed farmers to convert fallow low productivity land into productive land. With water availability, farmers firstly increased the cropped area and also were able to extend the cropping season, on the one hand, to raise multiple crops while cultivating more water-intensive crops such as vegetables and flowers, which are usually more profitable. The shift in cropping patterns towards cash crops was also notable for this period (Verma et al., 2023). Overall, the data clearly indicates that the availability of water for irrigation played a crucial role in enhancing the cropped area and extending the cropping season. Moreover, with assured water availability, farmers were able to

cultivate a wider range of crops throughout the year, which resulted in a significant increase in the overall area under cultivation.

Fig 4. Comparison of agricultural land between before and after recycling period Data source: Department of Agriculture and Horticulture, Kolar.



3.2.2 Increase in production and revenue of cereals and pulses

3.2.2.1 Finger millet

Finger millet, popularly known as ragi, holds a significant position as a staple food in South Karnataka, with a majority of the population relying on it for sustenance. Karnataka boasts the largest area dedicated to finger millet cultivation in India, making it the country's top producer of this crop. The cultivation of ragi is carried out using both rainfed and irrigated methods, with marginal and small farmers being the primary cultivators. Ragi is grown as both a single crop and intercrop, and it is one of the principal cereals cultivated in Kolar district (Bellundagi et al., 2016). According to **Fig. 5 (a)**, the production of finger millet has significantly increased during the after-recycling period compared to the before-recycling period. Specifically, the average annual production of finger millet was 6,631 tonnes during the before-recycling period, but it increased to 14,047 tonnes during the after-recycling period, presenting a >2-fold increase. The average production increase observed over the

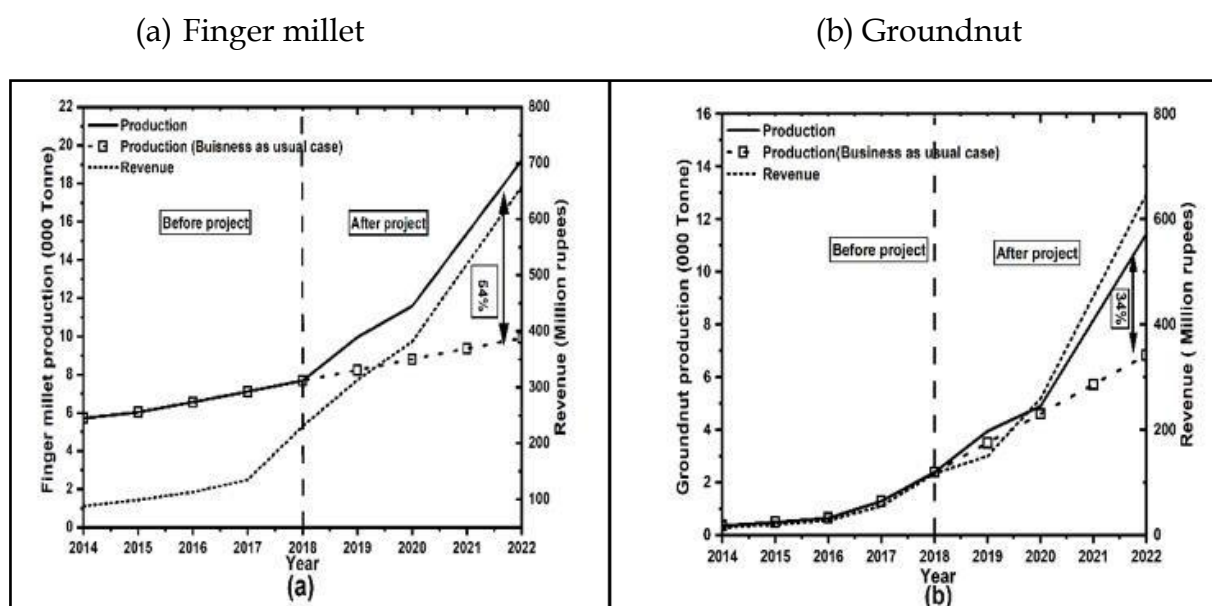
business-as-usual case was around 54%. This increase in finger millet production has a positive impact on the agricultural economy, as the revenue from finger millet has significantly increased as well as on-farm food security. In 2014, the revenue was ₹89 million, which increased to ₹659 million in 2022, indicating a substantial jump in revenue. Furthermore, the average annual revenue during the before-recycling period was ₹134 million, which increased to ₹469 million during the after-recycling period, presenting almost a 3-fold increase in economic benefit. This observed increase in production and revenue can be explained by several factors presented in **Table 2**, including improved average yields per hectare (53%), expansion of the average cropped area (14%), and an increase in the average selling price (88%) between before and after-recycling periods and also an increased level of household grain stock and its potential for being sold in the market. These data clearly indicate that the availability of irrigation water has played a significant role in boosting the production of finger millet and related food security.

3.2.2.2 Groundnut

Groundnut, known as the king of oil seeds, is an important legume crop in southern India, particularly in Karnataka, where it is extensively cultivated using rainfed and protected irrigation methods. Its versatility and numerous benefits have made it an essential crop, mainly for improving soil fertility (Reddy et al., 2020). **Fig. 5 (b)** indicates that water availability has a significant impact on groundnut production and revenue accrued. On an average, the annual production of groundnut increased from 1,028 tonnes to 6,863 tonnes, presenting a 6-fold increase from before-recycling to after-recycling period. However, the average increase in production was around 38% from the business-as-usual case. In addition to increased production, a substantial increase in revenue was also observed. Before recycling period, the average annual revenue was ₹47 million, but after recycling, it jumped to ₹378 million, presenting an almost 8-fold increase in economic value. The observed increase can be attributed to a combination of three key factors including improved average yields per hectare

(241%), expansion of the average cropped area (96%), and an increase in the average selling price (24%) between before and after recycling period (**Table 2**).

Fig. 5 Pattern of production and revenue with business-as-usual case for cereals and pulses



Source: Authors' estimates based on data from Department of Agriculture, Kolar.

3.2.3 Increase in production and revenue of vegetables

3.2.3.1 Green leafy vegetable

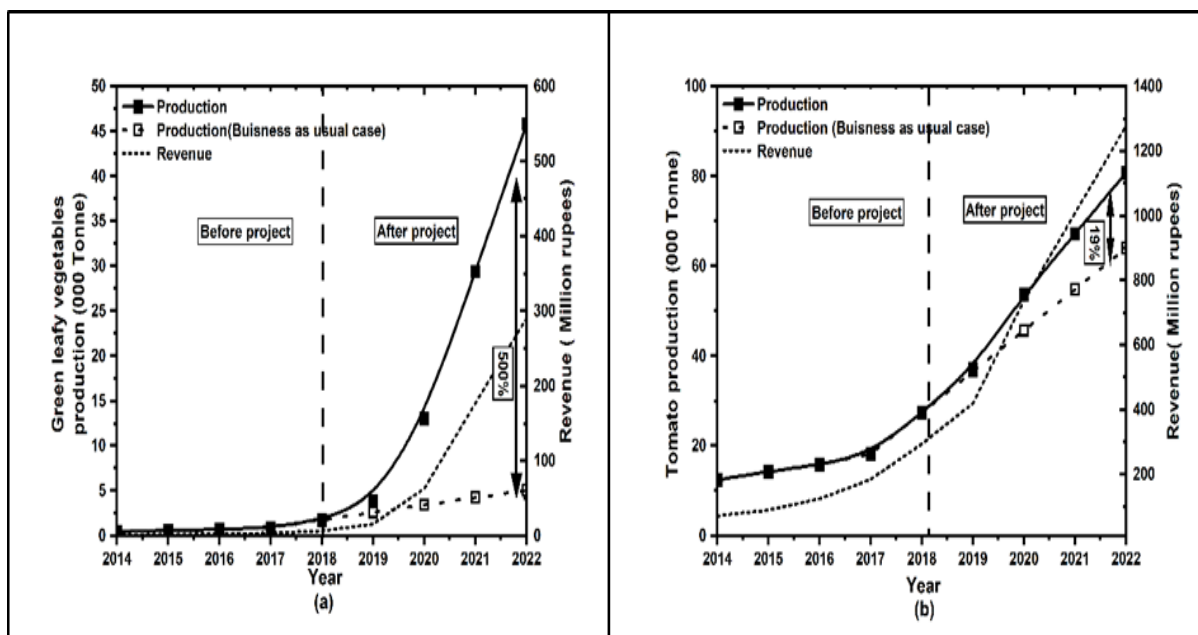
Fig. 6 (a) shows a significant increase in the production of green leafy vegetables after- recycling period as compared to the before-recycling period. Specifically, it was observed that the average annual production of green leafy vegetables was 894 tonnes during the before - recycling period, while it increased to 23,052 tonnes during the after-recycling period. This indicates a staggering 26-fold increase in production. However, the average increase in production was observed to be around 500% over the business-as-usual case. Furthermore, the increase in production of green leafy vegetables has a positive impact on the agricultural economy, as it has resulted in a significant increase in revenue. In 2014, the revenue from green leafy vegetables was `2 million, while in 2022, it increased to `290 million, indicating a significant jump in revenue. However, on an average before- recycling period showed annual revenue `3 million but after recycling, it jumped to `136 million, presenting almost 45 times jump in economic benefit. The observed increase can be attributed to a combination of factors presented in **Table 2** including improved average yields per hectare (152%), expansion of the average cropped area (473%, increase from 283 to 1622 ha), number of crops raised in a year (cropping intensity) and an increase in the average selling price (54%) between before and after recycling period. The data clearly indicates that the availability

of irrigation water has played a significant role in boosting the production of green leafy vegetables. By providing farmers with assured water resources such that it becomes possible to cultivate water-intensive crops green leafy vegetables throughout the year (multiple times in a year), which reduces the dependence on seasonal variations and weather conditions.

3.2.3.2 Tomato

Tomato cultivation has been a major source of livelihood for farmers in Kolar Taluka and district for several decades. The district produces a large quantity of tomatoes annually, which are supplied to different parts of the country as well as exported to other countries. **Fig. 6 (b)** indicates that on an average, the annual production of tomatoes increased from 17,622 tonnes to 59,721 tonnes, presenting 3 times increase from before-recycling to after - recycling period. However, the average increase in production was around 19% from the business-as-usual case. In addition to increased production, a substantial increase in revenue was also observed. Before recycling period, the average annual revenue was ₹153 million, but after recycling, it jumped to ₹861 million, presenting almost 6-fold increase in economic value. The observed increase can be attributed to a combination of various key factors including improved average yields per hectare (69%), high yield variety, expansion of the average cropped area (73%, increase from 800 to 1384 ha), increased cropping intensity (**Table 2**) and an increase in the average selling price (75%) between before and after recycling period.

Fig. 6 Pattern of production and revenue with business-as-usual scenario for vegetables (a) Green leafy vegetables (b) Tomato



Source: Authors' estimates based on data from Department of Horticulture, Kolar.

3.2.4 Increase in production and revenue of flower cultivation

3.2.4.1 Chrysanthemum

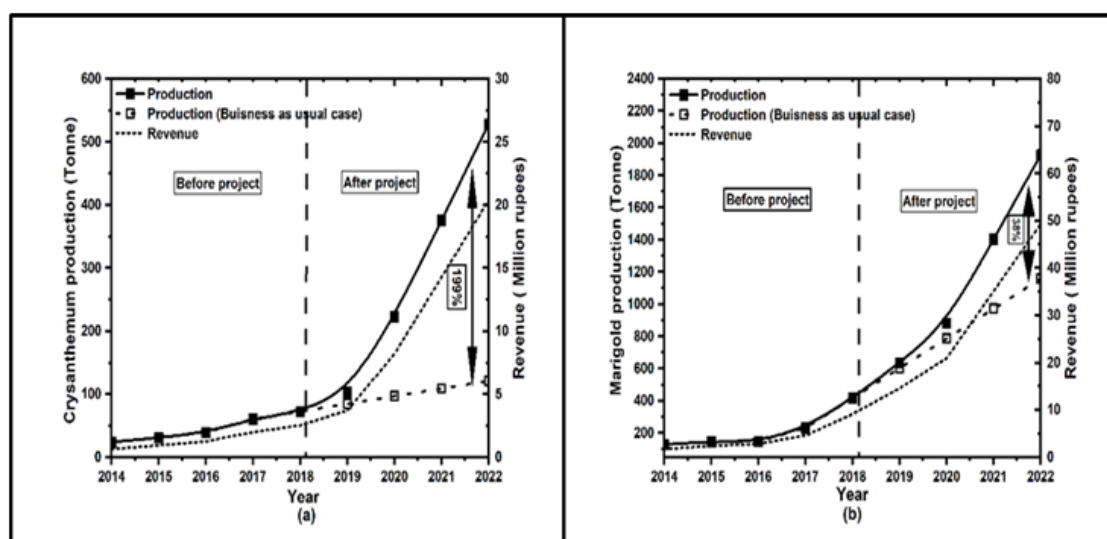
Fig.7 (a) indicates that there has been a significant increase in Chrysanthemum production during after the recycling period. The average annual production before- recycling was 45 tonnes, but it increased to 307 tonnes in after-recycling period. This means that there was a 7

-fold increase in production from before to after recycling. Furthermore, the data also indicates that there was a 199 % increase in average production compared to the business-as-usual case. This increase in production has a positive impact on revenue as well. Before the recycling period, the average annual revenue generated from Chrysanthemum production was `2 million. However, after the recycling period, the revenue increased to `12 million, which presents almost 6-fold increase in revenue. It is obvious that the increase in Chrysanthemum production during the recycling period is indeed due to an increase in yield hectare (214%), expansion of the average cropped area (45%) and cropping intensity (**Table 2**) and an increased average selling price (21%).

3.2.4.2 Marigold

Cultivation of Marigolds has been a popular agricultural practice in study area i.e., Kolar Taluka. Marigold cultivation was usually taken up on a small scale by local farmers, who rely on traditional farming practices. However, there is also a growing interest in commercial cultivation of marigold flowers due to the high demand in both domestic and international markets. **Fig. 7 (b)** presents that the average production of marigold experienced a significant increase in the after-recycling period. Specifically, it increased from 214 tonnes in before- recycling period to 1, 211 tonnes after-recycling, which presents a nearly 6 -fold increase in overall production at the Kolar Taluka. Furthermore, this increase was substantial when compared to the business-as-usual case, as it resulted in a 38% jump in production. Notably, the rise in production was accompanied by a significant improvement in revenue. The average annual revenue of marigold rose from `4 million before recycling to `30 million after recycling: a 7 -fold increase. The observed increase may be attributed to four key factors, namely, an improvement in average yields per ha by 304%, an expansion in the average cropped area by 27% and cropping intensity (**Table 2**), and an increase in the average selling price by 37% between the before and after recycling period. Overall, all, these results suggest that water availability has a positive impact on both productions, cultivated area, and intensity and revenue in the marigold industry.

Fig. 7 Pattern of production and revenue with business-as-usual scenario for flowers (a)Chrysanthemum (b) Marigold



Source: Authors' estimates based on data from Department of Horticulture, Kolar.

3.2.5 Increase in production and revenue from fruit cultivation

3.2.5.1 Papaya

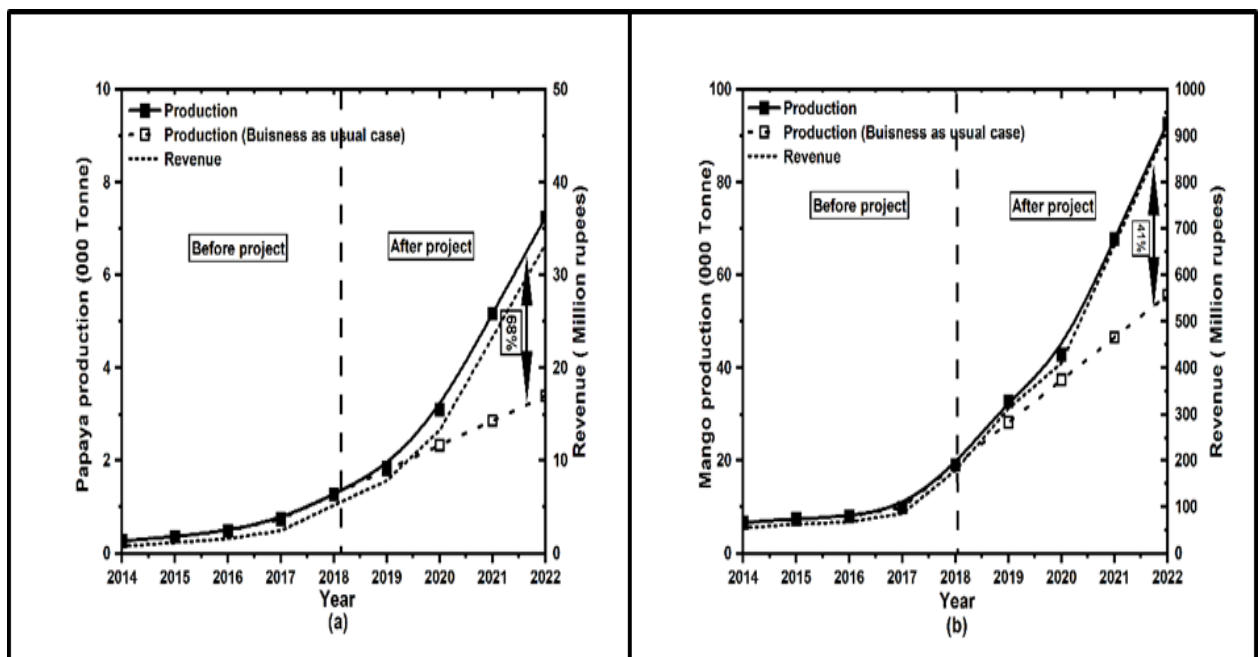
The data presented in the **Fig. 8 (a)** indicates a significant increase in papaya production during the before-recycling period. Specifically, the average annual production before-recycling of papaya increased from 628 tonnes to 4,350 tonnes after-recycling, which is almost a 7-fold increase. This increase in production is even more substantial when compared to the business- as-usual scenario, as it resulted in an 68% jump in production. Furthermore, the increase in papaya production has a significant impact on revenue. The average annual revenue of papaya increased from ₹2 million before recycling to ₹19 million in the after- recycling period. This presents a 9-fold increase in revenue and indicates substantial economic benefits. The observed increase may be explained in terms of increases in average yields per ha by 313%, cropped area by 41% and cropping intensity (**Table 2**), and average selling price by 35% between the before and after recycling periods. Papaya plants require a consistent supply of moderate watering to support its growth and development. Overall, these results highlight the positive impact of water availability on papaya cultivation, leading to increased production and revenues.

3.2.4.2 Mango

Mango is the single largest fruit crop raised in Kolar Taluka. The data presented in the **Fig. 8 (a)** indicates a significant increase in mango production

in the after-recycling period. Specifically, the average production of mango increased from 10,230 tonnes before recycling to 59,092 tonnes in the after-recycling period, presenting nearly a 5 -fold increase in production. Furthermore, this increase in production resulted in a 41% jump in production compared to the business-as-usual case. Moreover, the increase in mango production has a significant impact on revenue. The average annual revenue rose from `90 million before recycling to `577 million in the after-recycling period. This presents almost a 6-fold increase in revenue and highlights the economic benefits resulting from the increased mango production. The rise in production and revenue can be explained by the significant increase of 258% in yields per hectare, along with a 40% expansion in cropped area and a 13% growth in the average selling price between before and after recycling period (Table 2).

Fig. 8 Pattern of production and revenue with business-as-usual scenario for fruits (a) Papaya (b) Mango



Source: Authors' estimates based on data from Department of Horticulture, Kolar.

Table 2 Area, productivity and total annual production of different crops

	Before Recycling				After Recycling				Change in Area (%)	Change in Productivity (%)
	Cultivated area (ha)	Avg. yield/crop (tonne/ha)	Cropping intensity(No. of crops /year)	Avg. total production (Thousand tonne)	Cultivated area (ha)	Avg. yield/crop (Tonne/ha)	Cropping intensity(No. of crops /year)	Avg. total production (Thousand tonne)		
Finger millet	7686	1.71	1	13	8762	2.61	3	68.76	14	53
Groundnut	652	2.10	1	1.30	1281	7.17	2	18.39	96	241
Green leafy vegetable	283	8.12	2	4.52	1622	20.51	6	199.64	473	153
Tomato	800	38.85	2	62	1384	65.57	3	271.24	73	69
Chrysanthemum	95	1.75	2	0.33	138	5.50	3	2.27	45	214
Marigold	145	2.39	2	1.56	185	9.66	4	5.36	27	304
Papaya	114	11.91	1	1.3	160	49.20	2	15.74	41	313
Mango	3156	4.60	1	14.54	4418	16.53	1	73.03	40	258

Source: Authors' estimates based on data from Department of Agriculture and Horticulture, Kolar.

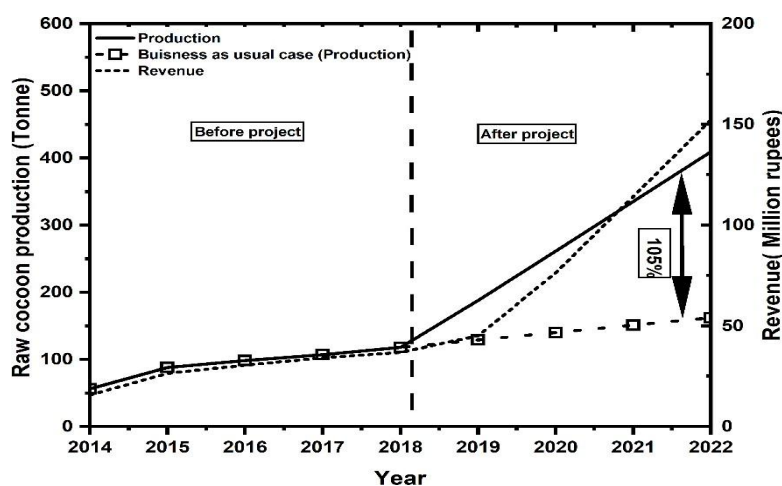
3.2.5 Increase in production and revenue from sericulture sector

3.2.5.1 Raw cocoon outputs

The production of raw cocoons is a crucial aspect of the thriving sericulture industry in Kolar Taluk and district, which is particularly renowned for its production of high-quality mulberry silk. Increased water supply is expected to increase the window over which firstly mulberry is cultivated and thereby the number of mulberry crop cycles (and cocoon rearings) that can be taken up by a farm-family in a year. It may be seen from **Fig.9**, that there has been a substantial increase in cocoon production in study area during after recycling period. Before-recycling period, the average annual production of cocoons was 93 tonnes, which increased to 298 tonnes in the after-recycling period. This presents a remarkable 3-fold increase in production. Additionally, there was a 105% increase in production as compared to business-as-usual case. This increase in cocoon production has not only contributed to the growth of the sericulture industry but has also generated significant economic benefits. The average annual revenue from raw cocoon production was `28 million before the recycling period, which increased to `97 million in the after-recycling period. This indicates a 3-fold increase in economic benefit. The increase in raw cocoon production can be attributed to the improvement in the cultivation of mulberry

plants and the duration for which leaves can be harvested. Mulberry plants are the primary source of food for silkworms, and the quality and quantity of mulberry leaves significantly influence the productivity and quality of the cocoons. The combination of increase in mulberry and cocoon production and revenue shows a positive impact on the local economy and the overall well-being of the community.

Fig. 9 Pattern of production and revenue with business-as-usual scenario for raw cocoon



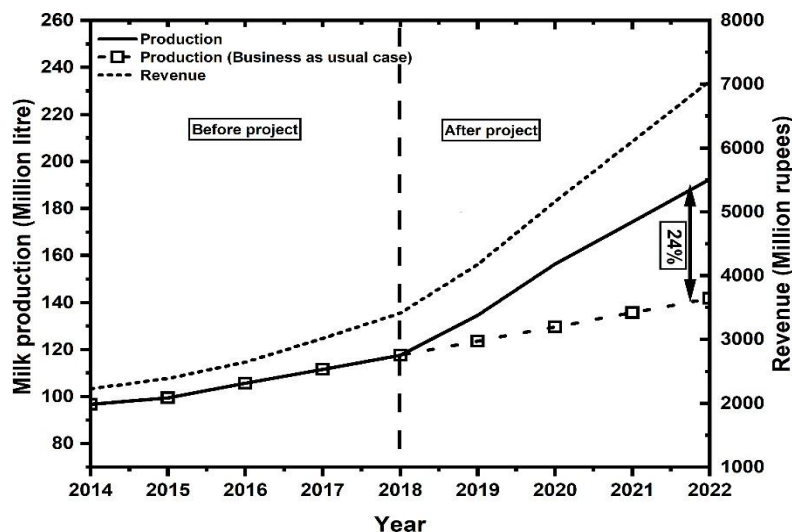
Source: Authors' estimates based on data from Department of Sericulture, Kolar.

3.2.6 Increase in production and revenue from milk

The production of milk is a crucial aspect of the agricultural economy in many regions, including present study area. **Fig. 10** indicates a substantial increase in milk production in the after-recycling period. The average milk production during in the -recycling period was 106 million liters, which increased to 164 million liters during the after-recycling period, presenting 1.5 times increase in milk production. There was a 24% increase in observed production as compared to the business-as-usual scenario. Apart from the increase in milk production, there was also an observed increase in the average revenue generated from the sale of milk. The revenue increased from ₹2,736 million in the before-recycling period to ₹5,622 million in the after-recycling period. This presents a significant 2-fold improvement in economic benefit. The improvement in milk production may be attributed to several factors, including the increase in cattle rearing and the availability of better-quality and quantity of fodder grasses due consistent and year-round water availability. Furthermore, the availability of better-quality fodder grasses plays a crucial role in the growth of milk production. It is also important to note that KOMUL is the largest procurer of milk in the Taluka. However, it there is now a trend among farmers to also supply milk to private dairies and therefore the impact in the after- recycling period may be expected to be more than provided by the

data collected from KOMUL. From several officers involved in milk procurement the fraction of milk collected by KOMUL was estimated to be 70% of the overall production. The overall benefit to the milk sector may thus be corrected using this factor, however, a more detailed survey would be required to assess the actual production.

Fig. 10 Pattern of production and revenue with business-as-usual scenario for milk



Source: Authors' estimates based on data from Kolar-Chikkaballpura District Co-operative Milk Producers Union Ltd. (KOMUL).

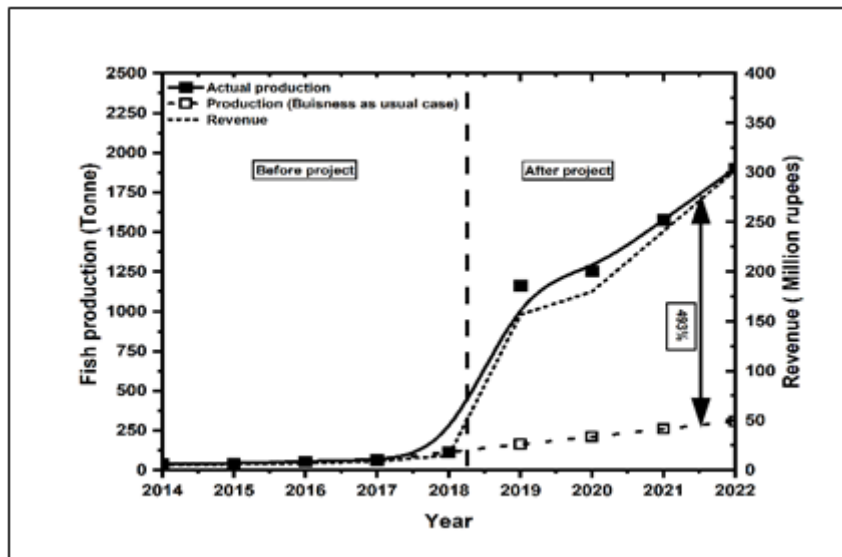
3.2.7 Increase in production and revenue of fish farming

Surface tanks in Kolar Taluka have traditionally been used for fish rearing. In the before- recycling period, assured levels of water in the tanks could be found only between August to January-February period allowing only for a 5-month growth period. These being irrigation tanks, water would be used for crop irrigation reducing the volume of water stored. Further, due to the high evaporation losses, nearly 75% of the water volume in these would be taken out by January-February period. The fish stocking density in the remaining 25% water in these tanks would be low leading to lower growth levels as well as body weight at harvest. However, in the after-recycling period had the surface tanks almost always round the year full thereby increasing the potential growth period to nearly 10-11 months a year while also keeping a full tank (water volume) round the year thereby allowing for higher stocking density as well providing for rapid increase in body weight. Both these contribute to increased capacity for fish production. **Fig. 11** indicates a significant increase in fish production in the after-recycling period. In the before-recycling period, the average annual fish production (nearly all the fish is caught) was 63 tonnes,

while in the after-recycling period, it increased significantly to 1398 tonnes, presenting an enormous 22 times increase in production. Compared to the business- as-usual scenario, the production showed a remarkable 493% jump. Moreover, the increase in fish production also has a substantial impact on revenue generation. The average revenue generated from selling fish in the before-recycling period was `8.5 million, which increased significantly to `210 million during the after-recycling period. This presents a significant 25 times hike in revenue generation.

The improvement in fish production may be attributed to several factors as discussed above, mainly due to the increase in water availability duration in the waterbody allowing for increased growth period and higher stocking densities. The recycled wastewater used in fish farming is somewhat richer in phytoplankton, zooplankton, and other nutrients such as nitrogen, phosphorus and potassium, which are essential for growth of aquatic flora, shelter and multiple trophic levels including increased food for fish growth (Zaibel et al., 2019; Zaibel et al., 2021; Sukhani & Chanakya, 2020). This combination creates an ideal environment for fish rearing, leading to improved fish growth and production while reducing risks. The growth in fish production has not only improved the overall economic conditions of the region but has also provided a reliable source of income for farmers and livelihoods to laborers involved in the fishing industry.

Fig.11 Pattern of actual production and revenue with business-as-usual scenario for fish



Source: Authors' estimates based on data from Department of Fisheries, Kolar.

3.3 Cost-benefit analysis

3.3.1 Net present value (NPV)

NPV is a financial metric used to determine the profitability of an investment project by comparing the total benefits generated by the project with its total costs (Shou, 2022). In the present study, the various benefits associated with the recycling project are presented in **Table 3**, which include revenue generated from the sale of agricultural, raw cocoon, milk, and fish production. To calculate the NPV, the discount rate 'r' is assumed to be 5% and the project lifespan is assumed to be 25 years. Based on this consideration, the NPV for the project is calculated and presented in **Table 4**. The NPV is found to be `40,100 million @5% interest rates on FCC and `27,103 million @ 8% interest rates, which is greater than 0. This indicates that the recycling project is financially sound and can be considered a profitable investment opportunity (Senante et al., 2011; Wang, 2021). The positive NPV calculation implies that the benefits of the recycling project outweigh its costs, indicating a potential for generating long- term and sustainable economic benefits.

Table 3. Benefit from different sectors (Year-2022)

Category	Sector	Production (Tonne) [1]	Market rates (Rs/Kg) [2]	Total gross average revenue (million rupees) [3] = (1*2)	Business as usual (million rupees) [4]	Total benefit (TB)(million rupees) [5] = (3-4)
W	Agriculture (crops)	2, 59, 417	Yearly avg. rates	3,872	2,020	1,852
X	Sericulture (cocoon)	409	Yearly avg. rates	152	47	105
Y	Dairy (milk)	192 (million liters)	Yearly avg. rates	7,049	5,002	2,047
Z	Fishery (raw fish)	1900	Yearly avg. rates	302	39	263
Benefit =W+X+Y+Z				11,375	7,108	4,268

Source- Department of Agriculture & horticulture; Department of Sericulture; KOMUL; Department of Fishery

3.3.2 Benefit-cost ratio (BCR)

The BCR is calculated by dividing the present value of benefits by the present value of costs, presented in **Table 4**. In this case, the BCR for the recycling project has been calculated and found to be 5.30 @5% interest rates on FCC and 4.26 @ 8% interest rates, which is quite impressive. This means that for every rupee invested in the project, there will be a return of 5.30 rupees in benefits

@5% interest rates. This indicates that the recycling project is financially viable and has the potential to generate significant returns on investment. Overall, the impressive BCR for the recycling project provides evidence that it is a financially viable opportunity with strong potential for economic success.

The results of the present study support previous research studies conducted by Godfrey et al. (2009), Senante et al. (2010), Verlichhi et al. (2012), Fan et al. (2015), Al-Sa'ed et al. (2015), Arborea et al. (2017), and Omole et al. (2019), which suggest that investment in reuse of treated wastewater has significant tangible and intangible benefits. This indicates that investing in wastewater recycling and reuse projects is a worthwhile endeavor especially for water stressed locations such as semi-arid tracts. For instance, a study conducted by Fan et al. (2015) in Beijing analyzed the cost-benefit analysis of the reuse of reclaimed water and found that the total benefit was 1.7 times greater than the total cost. Similarly, Verlichhi et al. (2012) conducted a cost-benefit analysis of the reuse of reclaimed water in Italy and found that BCR was 1.007. However, the present study found a higher benefit in terms of BCR, i.e., 5.30 @5% interest rates. Overall, the results of the present study provide further support for the potential benefits of investing in wastewater recycling and reuse projects, demonstrating that such investments can be financially sound and profitable.

Table 4. Calculation of net present value (NPV) and benefit cost ratio (BCR)

Year	BC Ratio and NPV @5% I (Million Rupees)					BC Ratio and NPV @ 8%I (Million Rupees)				
	Total benefit	Total cost	Discount factor	PV (TB)	PV (TC)	Total benefit	Total cost	Discount factor	PV (TB)	PV (TC)
1	0	661	0.95	0	630	0	779	0.93	0	721
2	629	661	0.91	571	600	629	779	0.86	540	668
3	1626	661	0.86	1404	571	1626	779	0.79	1290	618
4	2947	661	0.82	2424	544	2947	779	0.74	2166	573
5	4268	661	0.78	3344	518	4268	779	0.68	2905	530
6	4268	661	0.75	3185	493	4268	779	0.63	2689	491
7	4268	661	0.71	3033	470	4268	779	0.58	2490	455
8	4268	661	0.68	2889	447	4268	779	0.54	2306	421
9	4268	661	0.64	2751	426	4268	779	0.50	2135	390
10	4268	661	0.61	2620	406	4268	779	0.46	1977	361
11	4268	661	0.58	2495	386	4268	779	0.43	1830	334
12	4268	661	0.56	2376	368	4268	779	0.40	1695	309
13	4268	661	0.53	2263	351	4268	779	0.37	1569	286
14	4268	661	0.51	2156	334	4268	779	0.34	1453	265
15	4268	661	0.48	2053	318	4268	779	0.32	1345	246
16	4268	661	0.46	1955	303	4268	779	0.29	1246	227
17	4268	661	0.44	1862	288	4268	779	0.27	1153	211
18	4268	661	0.42	1773	275	4268	779	0.25	1068	195
19	4268	661	0.40	1689	262	4268	779	0.23	989	181
20	4268	661	0.38	1608	249	4268	779	0.21	916	167
21	4268	661	0.36	1532	237	4268	779	0.20	848	155

22	4268	661	0.34	1459	226	4268	779	0.18	785	143
23	4268	661	0.33	1389	215	4268	779	0.17	727	133
24	4268	661	0.31	1323	205	4268	779	0.16	673	123
25	4268	661	0.30	1260	195	4268	779	0.15	623	114
			Total	49416	9316			Total	35418	8316
			NPV	40100				NPV	27103	
			BC Ratio	5.30				BC Ratio	4.26	

Source: Authors' estimates based on data from different departments

Note: PV=present value

4. Conclusion

The present study presents a comprehensive CBA of treated wastewater-recycling projects for indirect GW recharge, with an emphasis on the economic valuation of tangible benefits. The study considers various cost categories, including wastewater treatment cost incurred by the BWSSB and water pumping cost incurred by the MI department. On the other hand, the benefit categories include the tangible economic benefits of revenues generated from sale of agricultural, horticulture, cocoon, milk, and fish production.

The results of the study reveal a significant increase in cropped land area and productivity during after recycling period. Increased and assured availability of water has led to significant increases in cropped area, cropping intensities, higher production in food, fruit, vegetable, and fruit crops, and in turn leading to very high jumps in revenues. Increased availability and assured supply of fodder and its security has created higher milk collection and related revenues while under a similar influence on mulberry cultivation has led to 6-fold increase in silk cocoon production. Tanks remaining filled round the year have increased the potential growth period, fish weight at harvest, and stocking densities leading to >25-fold increase in fish production and related revenues. The implementation of wastewater recycling projects increases revenue by boosting production and also has a positive impact on employment opportunity, improving access to markets, reducing transaction efforts, and increasing prices due to better quality products. Moreover, these projects promote sustainability, local economy, and environmental responsibility, leading to long-term benefits for both businesses and the wider community.

Furthermore, the cost-benefit analysis indicated that the calculated NPV is ₹40,100 million @ 5% and ₹27103 million @ 8 % interest rates on FCC, which is greater than 0, while the BCR is

5.30 (@ 5%) and 4.26 (@ 8%), confirming that the benefits exceed the costs of the recycling project. By focusing on the economic benefits of increased agricultural production and revenues, the study underscores the potential for these projects

to drive sustainable development and promote economic growth in water-scarce regions. The results provide evidence for policymakers that investing in wastewater recycling and reuse projects is a worthwhile endeavor due to their potential to address water scarcity, mitigate water pollution, create economic opportunities, and promote sustainable development. These types of projects can generate significant benefits for communities, businesses, and governments, making them a promising investment opportunity.

5. Acknowledgement

Gratefully acknowledge the Department of Minor Irrigation, the Government of Karnataka for providing data related to cost and financial support to carry out this research. Special gratitude to Shri C. Mruthyunjaya Swamy (Secretary to Government, Minor Irrigation & Ground Water Development Department) and Shri Krishna M (AEE, Department of Minor Irrigation) for their constant support. The authors acknowledge different government departments such as Department of Agriculture & Horticulture, Kolar, Department of Sericulture, Kolar, Chikkaballapur District Co-operative Milk Producer's Societies Union Ltd. Kolar, Department of Fishery Sciences, Kolar, for providing the necessary data. We also acknowledge support from the Bengaluru Water Supply and Sewerage Board (BWSSB). Thankful to the Council of Scientific & Industrial Research-Human Resource Development Group (CSIR-HRDG) for providing a research fellowship to the corresponding author. Also thankful to SERB-NPDF, Govt. of India for providing a research fellowship to one of the co-authors.

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Appendix 1: Weblinks to Unproven RM Therapies across Selected African Countries

Region/Pole	Country	Online RM vendors or clinics	Weblinks of such RM vendors/clinics
Western Africa	Nigeria	Yes	https://www.cystemcellcenter.com/stem-cell-treatment-in-nigeria/ https://glorywellnessng.com/ https://trtherapy.business.site/?utm_source=gmb&utm_medium=referral https://herennessa.com/ https://biocellclinic.com/
Western Africa	Senegal	Yes	https://mednourpro.com/stem-cell-therapy-in-senegal/
Western Africa	Ghana	Yes	https://www.c4hr.net/ https://www.nyamericainvestigation.com/
Western Africa	Côte d'Ivoire	Yes	Several clinics available but no website was found
Central Africa	Cameroon	Yes	https://www.stemcelltherapyinindia.com/stem-cell-treatment-for-cameroon-patients.html https://regenespine.com/regenerative-spine-joint-stem-cell-pro-treatment-cameroon-cm/ https://www.vaidam.com/knowledge-center/patient-testimonials/mother-travels-cameroon-stem-cell-procedure-finds-ideal-treatment-her-child
Central Africa	Republic of Congo	Yes	https://www.stemcelltherapyinindia.com/stem-cell-treatment-for-congo-patients.html https://www.vierde.com/
Central Africa	Angola	Yes	https://web.facebook.com/SAUMOR_CONSULTORIO_MEDICO/
Central Africa	Gabon	None	
Southern Africa	Lesotho	Yes	https://www.indoamericanhealth.com/stem-cell-treatment-in-lesotho.html
Southern Africa	South Africa	Yes	https://sasstemcells.co.za/ https://www.stemcellclinic.co.za/ https://capetownstemcellcentre.co.za/
Southern Africa	Botswana	Yes	Several clinics available but no website was found
Southern Africa	Namibia	Yes	https://www.stemcellnamibia.com/
Northern Africa	Tunisia	Yes	https://www.lythoit.com/hospitals/stem-cell-therapy-hospitals-and-posts-in-tunisia/
Northern Africa	Egypt	Yes	https://www.vaidam.com/hospitals/orthopedics/orthopedic-stem-cell-treatment/egypt https://r3stemcell.com/egypt/
Northern Africa	Morocco	Yes	https://www.stemcellsgroup.com/global-stem-cells-group-opens-new-medical-office-casablanca-morocco/ https://www.mymeditravel.com/stem-cell-therapy-procedures-in-morocco
Northern Africa	Algeria	Yes	Several clinics available but no website was found
Eastern Africa	Ethiopia	Yes	https://www.placidway.com/profile/2017/PlacidWay-Ethiopia https://www.globalstemcellcare.com/ethiopia/ https://www.mesgoir.com/ethiopia/all/stem-cell-therapy/all/doctors
Eastern Africa	Kenya	Yes	https://vitalityroomstemcell.com/wound-care-stem-cells-in-kenya/ https://www.the-star.co.ke/health/2020-09-07-stem-cell-therapy-now-available-in-kenya/
Eastern Africa	Uganda	Yes	https://aifetolivenow.business.site/?utm_source=gmb&utm_medium=referral https://stemcell-therapy-ukina-cell.business.site/ https://www.gannutritioninternational.com/
Eastern Africa	Rwanda	Yes	https://www.ivocare.com/hospitals/medibest-hospital-kigali-rwanda/?locale=en&procedure_name=Cancer https://regenespine.com/regenerative-spine-joint-stem-cell-pro-treatment-rwanda-rw/

Varieties of regional innovation systems (RIS) around the world and catch-up by latecomers

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Abstract

This study identifies the characteristics and types of the regional innovation systems (RIS) of regions and cities in emerging economies in comparison to those in advanced economies. It uses the citation data of the US patents filed by 30 regions. Some RIS variables are newly developed, and they include intra-regional, inter-regional, and inter-national sourcing of knowledge and local ownership of innovation. The cluster analysis of these variables enables us to identify four major types of RIS around the world and link them to regional economic performance. The four types are, in the descending order of their per capita income levels, as follows: large, mature RIS characterized by a combination of long cycle technology specialization and high local ownership (Group 1), mixed RIS characterized by a long cycle and low local ownership (Group 2), “strong catch-up” characterized by short cycle and high local ownership (Group 3), and “weak catch-up” characterized by short cycle and low local ownership (Group 4). Groups 3 and 4 include only the regions in emerging world. They similarly specialize in the same short cycle time of technologies (CTT)-based sectors but show different records of economic performance. The key differentiating variable is the degree of local ownership of knowledge, which can be a basis for increasing domestic sourcing of knowledge and sustained catching up. Another important variable is decentralization, of which the level is lower in the strong catch-up group than in the weak catch-up group. In this Group 3, catching up is led by big businesses. Several cities experiencing upgrading, like Moscow, Beijing, and Shanghai, also show an increasing trend of local ownership and centralization.

Keywords: regional innovation systems, innovation, patents, latecomer, economic catch-up JEL code: C23, O31, O32, O33, O50, R11, R58

1. Introduction

Innovation systems has become a key concept in Schumpeterian economics since they were first proposed by Freeman (1987) and later at national levels by Lundvall (1992) and Nelson (1993). Lundvall (1992) defines national innovation systems (NIS) as “elements and relationships which interact in the production, diffusion and use of knowledge rooted inside the borders of a nation state.” Various dimensions of NIS have been introduced to analyze their relationship with economic growth (Archibugi & Coco, 2004; Castellacci, 2008, 2011; Edquist, 1997; Fagerberg & Srholec, 2018; Fagerberg & Verspagen, 2002; Lee & Lee, 2019). The concept of innovation systems has also been applied at the regional level, given the uneven distribution of innovations even in the same nation (Asheim et al., 2019). The regional innovation system (RIS) approach explains the heterogeneous distribution of innovation in the territory and aids in constructing policies enhancing the innovation capability of regional economies (Isaksen et al., 2018).

Cooke et al. (1998: 1581) define RIS as a “regional level system in which firms and other organizations are systematically engaged in interactive learning through an institutional milieu characterized by local embeddedness.” Various studies have been conducted on the relationship between knowledge, innovation, and economic growth in regional bases (Andersson & Karlsson, 2007; Capello et al., 2009; Harris, 2011; Huggins & Thompson, 2015; Rodríguez-Pose & Crescenzi, 2008). In particular, Rodríguez-Pose and Crescenzi (2008) analyze the impact of innovation on regional economic performance in Europe to find the importance of localized structural and institutional factors that shape the innovation capacity of a specific geographical context.

Furthermore, various RIS studies have explained a typology and dynamic change of RIS and show a variety of criteria and perspectives on the RIS (Asheim et al., 2019; Asheim & Gertler, 2006; Asheim, 1998; Cooke, 2001, 1998, 2005). Quantitative approaches have also been used to study the efficiency of different kinds of RIS (Fritsch & Slavtchev, 2011; Zabala-Iturriagagoitia et al., 2007). However, these studies are mostly for the regions in advanced countries; especially quantitative ones, involving latecomer regions are insufficient. In the literature, “peripheral or immature” RIS rely highly on foreign knowledge because of the lack of the indigenous knowledge or regional embeddedness and low level of regional embeddedness (Asheim et al., 2019; Hassink, 2001; Park & Markusen, 1995; Rodríguez et al., 2014).

Latecomers’ reliance on foreign knowledge is unsurprising considering that typical latecomer economies tend to achieve economic growth by relying on FDI and learning from foreign MNCs (Amsden & Chu, 2003; Bernardes & Albuquerque, 2003; Lebdioui et al., 2021). Any process of catching up a region in emerging economies may involve reduced reliance on foreign knowledge

and increased consolidation of local knowledge bases. Taking this reasoning as an initial motivation, we find out how different RIS of catching-up regions have been compared with those of advanced regions. This study is an attempt at quantitative analysis of RIS of 30 regions/cities around the world to identify the differentiating characteristics of catching-up RIS from the emerging world, using patent-citation-based measurements of diverse aspects of RIS. One of the key questions is what are the several types and pathways for catching-up development by latecomer regions.

Some studies discuss the typology of RIS although majority of them are about regions in advanced countries (Cooke, 1992) or use qualitative analyses. Some quantitative studies include Zabala- Iturriagagoitia et al. (2007), which evaluates RIS performance in terms of technical efficiency for Spanish case, and Fritsch and Slavtchev (2011), which suggests alternative measures for the efficiency of RIS based on the concept of a knowledge production function for German case. Nonetheless, quantitative analysis of RIS typology for emerging economies remains lacking, especially global analysis involving cities in both developed and developing world using a consistent framework and methodology.

In the meantime, empirical studies of NIS in both developed and developing countries have blossomed in the last decades. Some of them have focused on categorizing several types of the NIS by income level (Castellacci, 2011; Lee, 2013; Lee et al., 2021). Castellacci (2011) and Lee et al. (2021) use cluster analysis with variables representing the country's innovation systems. Using the five variables proposed in Lee (2013, Chapter 3) to measure the NIS, namely, knowledge localization, technological diversification, specialization in terms of CTT, originality, and knowledge decentralization (or concentration), Lee et al. (2021) make an interesting typology of NIS. The typology identifies several types of NIS, such as balanced and mature NIS, imbalanced and catching-up NIS specializing in short CTT-based sectors, and imbalanced and trapped NIS specializing in long CTT-based sectors. We adopt and further modify this empirical methodology for a region-level analysis.

Some case studies of RIS in several cities/regions have already used the similarly developed methodology. Although some of the above variables were first introduced in the early works of Jaffe et al. (1993) and Jaffe and Trajtenberg (2002), they were first utilized for the analyses of RIS in Wong and Lee (2021) for South Korea and Taiwan; Kim and Lee (2022) for Taipei, Penang, and Shenzhen; and Wong et al., (2022) for Singapore, Dublin and Penang. One of the methodological contributions of these RIS analyses is to decompose the national-level localization of knowledge creation and diffusion into the two components of intra-regional localization or local sourcing and inter-regional localization, where the latter refers to a region's innovation sourcing knowledge from other regions in the same nation and may be called inter-

regional sourcing, compared to the former or intra-regional sourcing. Furthermore, Kim and Lee (2022) introduce the variable of local ownership (of innovations) into RIS analysis and confirm its importance as a key determinant of long-term innovation performance of regions.

Kim and Lee (2022) differentiate two pathways of catching-up regions, namely, fast catch-up in Shenzhen, China and slow catch-up as in Penang, Malaysia. The explanation focusing on local ownership is that Shenzhen's faster catch-up is due to its increasing local ownership of knowledge with the rise of locally owned big businesses. By contrast, Penang's slower catch-up has to do with its continued reliance on MNCs but failing to promote local ownership of knowledge at the hand of locally owned companies. The analysis in this paper intends to see if these findings from related case studies of several regions' RIS can be generalized by analyzing a larger data set of RIS involving 30 cities around the world.

An analysis with a larger data set of RIS also enables us to identify varieties of RIS around world, differentiating regions in advanced economies from those in emerging economies. In particular, we can identify two types of RIS in the emerging world, with different degrees of local ownership corresponding to different levels of per capita GDP (gross regional domestic product or GRDP). In terms of empirical methods, we use cluster analysis to classify the 30 regions into different clusters in terms of several RIS variables. We then create a dummy for each of these clusters and use these dummies in growth regressions to match each to different speeds of economic growth.

In what follows, Section 2 discusses the literature and derives key hypotheses for empirical analysis. Section 3 discusses methodological issues, data, and measurement. Section 4 provides the results of the cluster analysis about RIS varieties and their changes over time and presents the regression analysis about the relationship between RIS types and economic growth. Section 5 focuses on several regions that have experienced changes in types and upgrading over time to reveal the dynamics and pathways for upgrading and catching up. The last section concludes the paper with a summary and remarks.

2. Literature review, theoretical issues, and hypotheses

Various RIS studies explain a typology and dynamic change of RIS and show a variety of criteria and perspectives on the RIS (Asheim et al., 2019; Asheim & Gertler, 2006; Asheim, 1998; Cooke, 2001, 1998, 2005). Asheim (1998) proposes three types of RIS, such as territorially embedded RIS, territorially networked RIS, and regionalized NIS. Cooke (2001) propose two types, namely, entrepreneurial and institutional RIS. Others propose a place-based leadership approach (Beer & Clower, 2014; Benneworth et al., 2017). Research on RIS typology for emerging economies as well as generalized typology covering

various regions over the world is lacking, yet effort has been exerted to conceptualize RIS in emerging economies.

Localization of knowledge sourcing

The concept of peripheral or immature RIS focuses on its high reliance on foreign knowledge and lack of the indigenous knowledge (Asheim et al., 2019; Hassink, 2001; Park & Markusen, 1995; Rodríguez et al., 2014). Latecomer economies tend to achieve economic growth by relying on FDI and learning from foreign MNCs (Amsden & Chu, 2003; Bernardes & Albuquerque, 2003; Lebdioui et al., 2021). This pattern indicates that latecomer regions show a low level of patenting and localization at early stages and more citations to foreign patents than indigenously owned patents even after they start to conduct their own R&D and file patents. We then hypothesize that catching-up regions show an increasing trend of local knowledge bases and regional embeddedness in creating and diffusing knowledge and, at the same time, a decreasing trend of their reliance on foreign knowledge bases.

Such a characterization of upgrading in the RIS of emerging economies is consistent with the theoretical arguments and evidence at the national-level studies of upgrading and catching up of emerging economies. Lee (2013) and Lee et al. (2021) confirm the trend of increasing localization of knowledge creation and diffusion, which is measured by national-level self-citation of a nation and how much knowledge is domestically created by citing the patents owned by the same nationality (Jaffe et al., 1993)¹. Therefore, one of the first tasks in this study is verifying such an upgrading at the level of regions or cities. However, a regional-level analysis needs modification. First, because a region may interact with other regions in the same nation, we have to decompose the national-level localization into intra-regional and inter-regional localization. The former may be called intra-region sourcing of knowledge, whereas the latter may be called inter-regional sourcing of knowledge. The remaining source is the international or foreign sourcing of knowledge.

The share of these three types of knowledge creation and diffusion, namely, intra-region (or local) inter-region (or national), and inter-national (or foreign) sourcing of knowledge, should be summed up to one because a patent from a region cites a patent from the same or different region in the same nation or a patent from other nations. Following Kim and Lee (2022), we define the three measures as follows:²

$$\text{Intra} - \text{regional sourcing}_{xt} = \frac{n_{xxt}}{n_{xt}}, \quad (1-A)$$

$$\text{Inter} - \text{regional sourcing}_{xt} = \frac{n_{xx^Ft}}{n_{xt}}, \quad (1-B)$$

$$\text{foreign sourcing}_{xt} = \frac{n_{xdt}}{n_{xt}}, \quad (1-C)$$

Where n_{xt} is the common denominator representing the total number of citations made by all patents invented in a region x' granted in year t . In Equation (1-A), n_{xxt} is the total number of citations to the patents invented in a region x made by the patents invented by region x and granted in year t . In Equation (1-B) $n_{xx^F t}$ is the total number of citations made to the patents invented in other regions (x') in the same nation made by all the patents from a region x . In Equation (1-C), n_{xdt} is the number of citations made to the patents invented in foreign nations (d) made by region x 's patents granted in year t .

We now use the patent data of 30 cities around the world to measure the above three measures of knowledge sourcing so as to verify the hypotheses that regions and cities in advanced countries show a high level of intra- or inter-regional sourcing of knowledge, whereas cities in emerging world show a low level of intra- or inter-regional sourcing of knowledge. Additionally, any catching up or upgrading of RIS in the emerging world should show an increasing tendency of intra- or inter-regional sourcing of knowledge, combined with a decreasing tendency of foreign sourcing.

The above hypotheses have already been confirmed by some scholars who have conducted comparative case studies of RIS in emerging economies, but they have yet to be generalized to a bigger data set. Wong and Lee (2021) confirm the increases in intra-region localization and decreases in reliance on foreign knowledge in the rapidly catching-up regions in Asia, namely, Hsinchu with its core firm of TSMC and Suwon with its core firm of Samsung. Kim and Lee (2022) confirm that Shenzhen has shown a faster increase of intra-region sourcing of knowledge than Penang, which is one of the reasons for the two cities' different speed of catching up, with Taipei as a reference city that has already achieved a status of a high-income economy.

Local ownership of knowledge and innovation

One puzzle arising from the comparative analyses of three information technology (IT) clusters in Asia, namely, Taipei, Shenzhen, and Penang, is how come Shenzhen and Penang correspond to different speeds of catching up, although they share the common origin of takeoff relying on FDI in the same industrial specialization into IT manufacturing. The above question is a puzzle in the sense that some existing works on technological catch-up, such as Park and Lee (2006) and Lee (2013), argue that latecomers achieve a fast catch-up if they specialize in short CTT-based and thus low entry barrier sectors, such as IT-based manufacturing. Prime examples are the past Korea and Taiwan and recent mainland China. Then, a question arises, that is, how can the different speeds of catch-up in the same short CTT specialized clusters across different economies.

The answer suggested by Kim and Lee (2022) is the different degrees of the rise in local ownership as learned from MNCs and after both regions, Shenzhen

and Penang. Local ownership of innovation made inside a region is important because some innovations (patents) are filed by an inventor in a region, but this inventor may be hired by a foreign MNC located in the region. Local ownership is high if there are more spinoff and spillover from the MNC and is an important indicator of technological catch-up. The share of local ownership in Taipei reached almost 100% by the mid-2000s from about 40% in the 1980s (Kim & Lee, 2022). The share of the local ownership in Shenzhen reached the similar level by the mid-2010 within a shorter period because the share used to be close to zero in the mid-1990s. By contrast, the local share in Penang did not show such a sharp increase, but it has remained around 10% since the 1990s.

In the above study, the variable of the local ownership of innovation measures the share of patents owned by indigenous firms out of all the patents invented in a region (with inventors' address in the same region) assigned to firms of all kinds of ownership. It can be defined as follows:

$$\text{Local ownership} = \frac{N_{cxt}}{N_{xt}} \quad (2),$$

where N_{cxt} is the number of patents invented in a region x and assigned to a firm with its nationality in the host country c , and N_{xt} is the total number of patents assigned to any firm and invented in a region (with the first inventor address located in region x) granted in time t .

We use the same variable to measure the degree of local ownership of 30 regions around the world and see if the differences in local ownership can explain the different performances in economic growth and upgrading of RIS. Cities in emerging economies can be really divided into two types, namely, the one with strong local ownership corresponding to a higher per capita income, and the other with low local ownership corresponding to a lower level of per capita income. Given that both groups show similarly short level of average CTT but are lower than cities in advanced economies, they can be named as "short CTT and strong local ownership" and "short CTT and weak local ownership" RIS.

Other dimensions of RIS

The preceding subsection has discussed the key hypothesis of this study, which is localization of knowledge creation and ownership. These aspects of localization complement and reinforce each other such that a high degree of local ownership facilitates further the increases in localization of knowledge sourcing. This is unsurprising because MNCs feel less need to conduct R&D in host countries and cities in the emerging world.

The current sub-section turns to other aspects of RIS that are addressed in empirical analysis. In this regard, we also consider several variables suggested

in the NIS study of Lee et al. (2021) but can also be measured and analyzed at a region level. Thus, the RIS analysis in this study uses the following three component variables: technological diversification, CTT, and innovation decentralization³. We briefly explain these NIS component variables, which are measured at the level of regions or cities. The details are available in Appendix 1.

The first variable for RIS analysis is technological diversification, which captures the degree to which a country or a region produces patents in a wide variety of technological fields. Technological diversification is about the width of the patent portfolio of a region/country and may be complementary to product or export diversification⁴. The second RIS variable is technological decentralization in knowledge creation across innovators. This variable refers to whether or not the producers of knowledge are led by a few big businesses or evenly distributed among a large number of innovators. We measure this degree of decentralization as 1 minus the HHI of concentration.

The third variable is to measure technological specialization by the variable called CTT, which is related to the question of whether countries specialize in sectors with rapid or slow obsolescence of knowledge. It refers to the average time lag between the grant years of the citing patents and that of the cited patents (Jaffe & Trajtenberg, 2002). Specifically, CTT refers to the extent to which a patent relies on recent or old technologies for the invention of new knowledge⁵. A short CTT indicates that the life span of the knowledge lasts only a few years, after which the usage dramatically declines as it soon becomes outdated or less used. In this sense, short CTT-based sectors correspond to low technological entry barriers against late entrants. Lee (2013) and Lee et al. (2021) find that successful latecomer economies, such as South Korea and Taiwan, tend to focus on sectors with short CTT, such as IT goods, during their rapid economic catch-up since the mid-1980s. By contrast, advanced countries tend to specialize in sectors with relatively long CTT, such as the pharmaceutical sector.

In the NIS literature, different characteristics of NIS are noted between advanced and catching-up countries (Lee, 2013; Lee et al., 2021). NIS in advanced countries tend to have all equally high values in all NIS variables, such as diversification, decentralization, and average CTT; in comparison, NIS in emerging economies tend to have low values in NIS component variables. We apply similar logics from the NIS literature to the RIS analysis and thereby try to differentiate RIS in emerging economies from that in advanced economies. Specifically, we hypothesize that RIS in high-income region group have high values in all RIS variables, such as high diversification, high decentralization, and long CTT specialization, in addition to high degree of local ownership and local sourcing of knowledge (= low foreign sourcing). By contrast, RIS in emerging economies are characterized as either all low values,

such as low diversification and decentralization and short CTT, or imbalances, like low diversification but very long CTT or vice versa⁶.

3. Measurement, data, and methodology

Methodological issues

If we summarize the discussion in the preceding section, our measurement of RIS consists of seven variables, some of which are newly suggested, whereas others are adoption of those used to measure NIS. The former includes the three variables representing intra-region, inter-region, and inter-national (foreign) sourcing of knowledge, plus local ownership of innovation. The latter includes technological diversification, decentralization, and CTT. These variables are measured using a single data set comprising patents filed in the US. The advantage of using such a data set is that the data sources are homogenous; thus, the variables are easily collected and measured consistently for different cities around the world. Such a method can also be justified given that the focus of analysis is not every spectrum of cities but only those located in the middle- or higher-income economies but tend to show varying degrees of innovation capabilities that can be measured by patent data.

Our empirical analysis utilizes the USPTO bulk data, i.e., a weekly released US patent panel data set containing a large number of information for the period of 1976–2017. To turn this bulk data into user-friendly forms, we follow Lee et al. (2021) to conduct data mining using the method of Potter and Hatton (2013)⁷. After this process, we measure the seven RIS component variables. We identify patents for each city in terms of the address of the first inventor of a patent.

One issue may be whether these seven variables are comprehensive enough to represent the diverse dimension of innovation activities of a region. There is a tradeoff between comprehensiveness associated with a large number of variables versus parsimoniousness associated with less burden on data requirements. Some of existing studies on NIS or RIS tend to use many and diverse indicators for different research orientations⁸. Our choice of these knowledge-related variables is close to the original definition of innovation systems, which is a mechanism to generate, diffuse, and utilize knowledge (see Lundvall's definition above and OECD, 1997). Another justification in using only these variables is Lee and Lee (2019), who develop a composite NIS index using these variables and show that it is a comprehensive enough predictor of economic growth and more robust than or equally robust as the index of economic complexity (Hausmann et al., 2014). In addition, Lee et al. (2021) conduct a cluster analysis of NIS typologies and show that the identified types of NIS explain well the different economic performances.

Sample of 30 cities

The data set in this study covers 30 regions and cities around the world, and Appendix Table 1 lists them, together with other basic information, such as the number of US patents, per capita GDP (GRDP), population, and so on. In Appendix Table 1, all variables are calculated as the yearly average value of each variable in the most recent period, 2013–2017. Given our focus on emerging economies and their regions, our criteria to select cities is a combination of innovation intensity measured by patent counts and representativeness of economies where the cities are located. For instance, in Asia, two giant economies, China and India, are considered first, so their innovation-intensive cities are included in the sample. Japan and the two east Asian tigers (Taiwan, and South Korea) are considered, and their innovation intense cities are chosen in consideration of patent counts. This is why Gyeong-gi province where Samsung is located as well as Daejeon, which is a hub city for many government research institutes, are included in the sample, in addition to Seoul.

We thus include 13 Asian regions, namely, Tokyo, Gyeonggi province in South Korea, Seoul, Osaka, Taipei, Beijing, Shenzhen, Daejeon in South Korea, Shanghai, Bangalore, Hong Kong, New Delhi, and Penang, in the order of the patents. The sample include three regions in Latin America, such as Sao Paulo in Brazil, Santiago in Chile, and Mexico City in Mexico. These cities are the top 3 cities in Latin America in terms of the patent counts. Johannesburg in South African is included to represent Africa.

Cities in advanced countries serve as a benchmark for emerging economy cities. First, for European cities, they are basically chosen to represent the four large economies of Germany, France, UK, and Italy, plus one Nordic country of Sweden. Therefore, we include seven European regions, which are Munich, Paris, Berlin, Cambridge (the UK), London, Stockholm, and Milan, in the descending order of the number of patents. Moscow is in Europe but is treated as an emerging country city as Russia belongs to the BRICS group and its per capita income is about 50% of that of the US. Similarly, Tel Aviv is located in middle east Asia but is treated as a city in advanced economy, given the uniqueness and high income status of Israel.

So far, patents are classified into different cities defined by their official administrative boundary and the address of the first inventor. For US regions and cities, different administrative practices require to merge several counties to define a bigger area. For instance, there is no such city as Silicon Valley, so we merge several counties into one unit called Silicon Valley. A similar practice is applied for other regions in the US (details are in Appendix 2). In terms of their patenting activities, the data set include four areas in the United States, namely, Silicon Valley area, Boston–Cambridge area (later referred to as Boston

for simplicity), Austin area, and Houston area, in the descending order of the number of patents.

Basically, most variables such as the regional GDP and population, are resourced from the Regional Economy in OECD. Stat database; otherwise, from each city, region, or country's statistics department website. The detailed information about the data resource is explained in Appendix 3.

Cluster analysis and growth regressions

We apply cluster analysis to these RIS component variables to classify the RIS of cities into several types. Cluster analysis is a method of grouping objectives by a pre-determined set of their attribute variables, revealing homogeneity of within-group and heterogeneity of between-groups. In cluster analysis, there are three methods of average linkage, single linkage, and complete linkage. We adopt the average linkage method, which is preferable to the single linkage or complete linkage methods because of their relative sensitivity to extremes or outliers (Jobson, 1992). The average linkage cluster analysis is based on Euclidean distance measurement, and this is determined by averaging the proximities between all pairs of objects, one object for each group (Jobson, 1992).

Using the results of cluster analysis, we create a dummy for each cluster and conduct growth regressions to match these cluster dummies to economic growth. We conduct regression analysis to adopt the method of system GMM estimation proposed by Arellano and Bover (1995) and Blundell and Bond (1998). This estimation is supposed to handle unobserved region heterogeneity, omitted variable bias, measurement error, and potential endogeneity by using explanatory variables as instrument variables. There is a possibility of over identification of instrumental variables because explanatory variables and their lagged variables are used as instrument variables. Therefore, we conduct Hansen test for over identification and AR (2) test for the second-order serial correlation of the residuals in differenced equation. In addition to the system GMM estimation, we conduct the least square dummy variable (LSDV) estimation to check the consistency of the regression results. The LSDV estimation is similar with the fixed effect estimation and controls the individual fixed effects (here, region-specific effects).

4. Varieties of RIS and their linkages to economic growth

Key RIS variables and cluster analysis leading to four types

Table 1 presents the basic innovation profiles of 30 cities and regions in terms of the values of the seven RIS component variables as annual averages for the 2013–2017 period. Paris is at the top with its highest GDP per capita, whereas Bangalore in India comes last. We have the annual values of these seven

variables for the 18 year period of 2000–2017. We then conduct cluster analysis to classify the 30 cities into several types. For this, we divide the whole period into two sub-periods, 2000–2008 and 2009–2017 as well as into five sub-periods to show dynamics over time. In the 5 sub-period division, the first period is from 2001 to 2004, the second period is from 2004 to 2007, the third period is from 2007 to 2010, the fourth period is from 2010 to 2013, and the fifth period is from 2013 to 2017.

[Table 1 and Figure 1]

Table 1 - Average values of RIS Variables by region (annual average for 2013-2017)

	Intra-regional sourcing	Inter-regional sourcing	Inter-national Sourcing	Local ownership	Relative cycle time	Diversification	Decentralization
Paris	0.0518	0.0724	0.8758	0.7524	1.075	0.277	0.8912
Silicon Valley	0.2432	0.5183	0.2385	0.894	0.8736	0.5869	0.8251
Boston Area	0.0905	0.6268	0.2827	0.9405	0.9921	0.4719	0.8738
Austin	0.0711	0.6802	0.2487	0.9133	0.9079	0.3577	0.8053
Houston	0.186	0.5668	0.2472	0.9524	1.1215	0.4123	0.8944
Tokyo	0.1488	0.3154	0.5358	0.9528	0.9694	0.6283	0.9384
London	0.0009	0.0411	0.958	0.5721	1.003	0.2304	0.8833
Milan	0.0341	0.0358	0.9301	0.6235	1.1449	0.2199	0.924
Cambridge	0.0242	0.0381	0.9377	0.465	1.0	0.1962	0.8887
Taipei	0.1027	0.07	0.8273	0.8522	0.8511	0.4989	0.8325
Stockholm	0.0253	0.0691	0.9056	0.7603	0.8791	0.1543	0.7859
Munich	0.0253	0.0894	0.8853	0.7329	1.0305	0.3133	0.9148
Hong Kong	0.0436	0.0096	0.9468	0.255	0.9996	0.337	0.8779
Tel Aviv	0.0289	0.0728	0.8983	0.4977	0.893	0.1721	0.8364
Moscow	0.0519	0.005	0.9432	0.3721	0.9518	0.1679	0.8409
Berlin	0.0375	0.0734	0.8891	0.7151	1.0798	0.2778	0.9148
Seoul	0.0656	0.0881	0.8463	0.9678	0.8529	0.482	0.8173
Mexico City	0.0131	0.008	0.9789	0.6077	1.2113	0.0592	0.8152
Osaka	0.1045	0.3863	0.5092	0.9628	0.9881	0.5129	0.8305
Shenzhen	0.0408	0.0208	0.9385	0.9247	0.8165	0.3455	0.673
Gyeonggi-do	0.1154	0.0642	0.8205	0.9794	0.822	0.5243	0.7888
Penang	0.0341	0.0096	0.9563	0.0838	0.9031	0.0854	0.8329
Beijing	0.0448	0.009	0.9462	0.5504	0.8076	0.3624	0.8248
Daejeon	0.0467	0.0586	0.8947	0.9876	0.9426	0.3552	0.7033
Shanghai	0.0258	0.0154	0.9588	0.5277	0.897	0.3573	0.8077
Sao Paulo	0.0131	0.0058	0.9812	0.3685	1.1164	0.0968	0.8444
Santiago	0.0242	0.0019	0.9739	0.693	1.2377	0.0613	0.7915
New Delhi	0.0146	0.0209	0.9646	0.1962	0.8279	0.1053	0.8609
Bangalore	0.0136	0.0115	0.9749	0.1082	0.787	0.2152	0.9171
Johannesburg	0.0215	0.0240	0.9545	0.6650	1.1823	0.0537	0.7212
Average	0.0581	0.1336	0.8083	0.6625	0.9722	0.2973	0.8385

Figure 1 Dendrogram of cluster analysis using 7 RIS variables

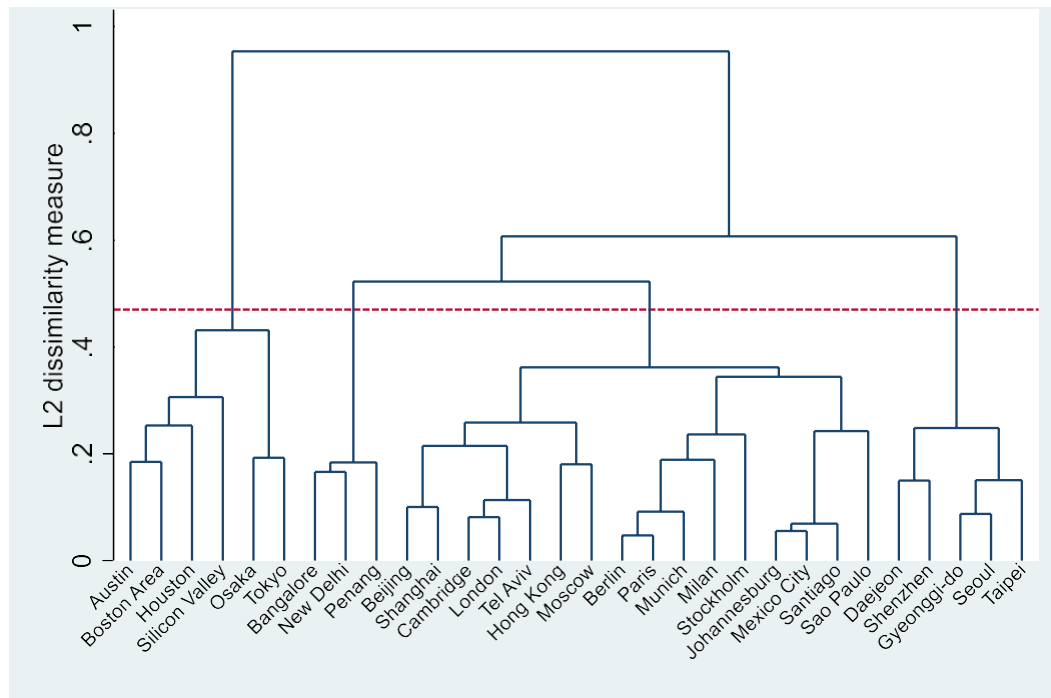


Figure 1 shows the dendrogram for the results of the cluster analysis for the recent nine-year sub- period, and Table 2 shows the results for the two sub-periods and the five sub-periods. In both results, we identify four major groups, although the member cities show variations over time or sub-periods. Table 2 presents the four groups in the descending order of the average per capita income of the constituent cities.

If we read the recent nine-year period results in Table 2A, Group 1 includes 6 cities in large, high income economies, such as four from the US (Austin, Boston, Houston, and Silicon Valley) and two from Japan (Osaka and Tokyo). Group 2 can be called a mixed group in that it includes not only eight cities from advanced economies (Berlin, Paris, Munich, Stockholm, Milan, Cambridge, Tel Aviv, and London) but also another eight cities from emerging economies (Moscow, Hong Kong, Shanghai, Beijing, Johannesburg Sao Paulo, Mexico City, and Santiago).

The next two groups, Groups 3 and 4, include cities in emerging economies only, although income levels and innovation performances vary. Group 3 corresponds to a higher per capita income than Group 4, and it includes Taipei, Seoul, Shenzhen, Gyeonggi-do (S. Korea), and Daejeon (S. Korea). Group 4 includes Penang, New Delhi, and Bangalore, which are all in Asia. The above classification results from the recent nine years is exactly the same as the results from the recent five years.

Table 3 summarizes the defining characteristics of each group in terms of the average values for the seven RIS variables, beside per capita income. First, the outstanding feature of Group 1 is the highest value of inter-regional sourcing (0.52), which seems to reflect that these cities are all located in a large economy with enough scope and diversity within a nation. We may call this group as “large, mature economy cities” or large mature RIS for simplicity. This group also boasts the highest intra-regional sourcing (0.14) of knowledge, indicating a high degree of local embeddedness of its innovation activities, represented by Silicon Valley (0.24 in Table 1). In addition, it shows the lowest degree of international sourcing of knowledge, reflecting its less dependence on foreign knowledge, which is matched by the highest ratio of local ownership (0.94) of innovations. Moreover, this group boasts a high degree of technological diversification, decentralization, and long CTT.

Group 4, corresponding to the lowest per capita GDP, seems to be exactly opposite to the Group 1 in that it features the lowest intra- and inter-regional sourcing (0.02 and 0.01, respectively) but the highest reliance on foreign knowledge (0.97) and lowest degree of local ownership (0.13). Its technological specialization is in short CTT (0.84: shortest among the four groups). As discussed in Section 2, short CTT specialization has not resulted in strong catching up in living standards of Group 4 cities, which seems to be attributable to its lowest degree of local ownership. This group seems to be consistent with the idea of the immature or peripheral RIS. They may thus be termed as “weak catch-up,” featuring a combination of short CTT and low local ownership.

In comparison, Group 3 corresponds to “strong catch-up” shown by its per capita income, which is more than two times higher than Group 4. Despite the similar specialization into short CTT, a differentiating factor is the high local ownership (0.94), which is as equally high as that of Group 1. Consistent with high local ownership, its dependence of foreign knowledge is the second lowest, after Group 1 (0.87), and its intra-regional sourcing of knowledge is the second highest (0.07).

Group 2 includes diverse cities around the world, and its per capita income and intra-regional sourcing are in between those of Groups 1 and 3. It shows the longest CTT. It also shows an equally high reliance on foreign knowledge and an equally low inter-regional sourcing, compared with Group 4. Although this group comprise cities from developed and emerging economies, two sub-groups of cities are not much different in terms of the values of RIS variables (see Table 3 for each sub-group cities from developed vs. emerging economies). Therefore, the average values of the whole Group 2 is not merely an average of heterogeneous cities but reflects well the characteristics of cities from both developed and emerging economies.

One simple way to characterize these four groups is a 2×2 combination of CTT and ownership. CTT is an important variable suggested in the NIS literature and in the RIS analysis. That both of the top two RIS group specialize in long CTT-based sector is interesting to note. By contrast, two RIS groups comprising cities in emerging economies only correspond to short CTT specialization. Figure 2A shows the trend of CTT in these four groups, indicating clearly that the top two lines correspond to Groups 1 and 2, whereas the bottom two graphs correspond to Groups 3 and 4.

Groups 1 and 2 correspond to higher incomes and long CTT, but Group 1 is a combination of long CTT and high local ownership, whereas Group 2 is a combination of long CTT and low ownership. By contrast, Groups 3 and 4 comprise emerging economy cities only and specialize commonly in short CTT. However, Group 3 features short CTT and high local ownership and boasts strong catch-up, whereas Group 4 features short CTT but low local ownership and corresponds to weak catch-up. Hence, we name Group 3 as short CTT and high local ownership; Group 4, short CTT and low local ownership.

Figure 2B shows the trend of local ownership in four groups, indicating clearly that only Group 3 (strong catch-up) caught up with Group 1. In addition, only Group 3 shows the decreasing trend of inter-national sourcing of knowledge and increasing sourcing of intra- and inter-regional sourcing of knowledge (Figure 2C, 2D, 2E) and technological diversification (Figure 2F). In terms of technological diversification, long cycle and high local ownership group (Group 1) is the most diversified among the groups with above 47% for all periods. Group 3 (short cycle and high local ownership) started from 31% in 2000–2002 period and increased to 42% in 2015–2017, which is close to the level of Group 1. Group 4 (short cycle and low local ownership) has the lowest level of ownership in all periods, although it shows some increasing trend and follows other groups.

Figure 2A Trends of Relative cycle time by group

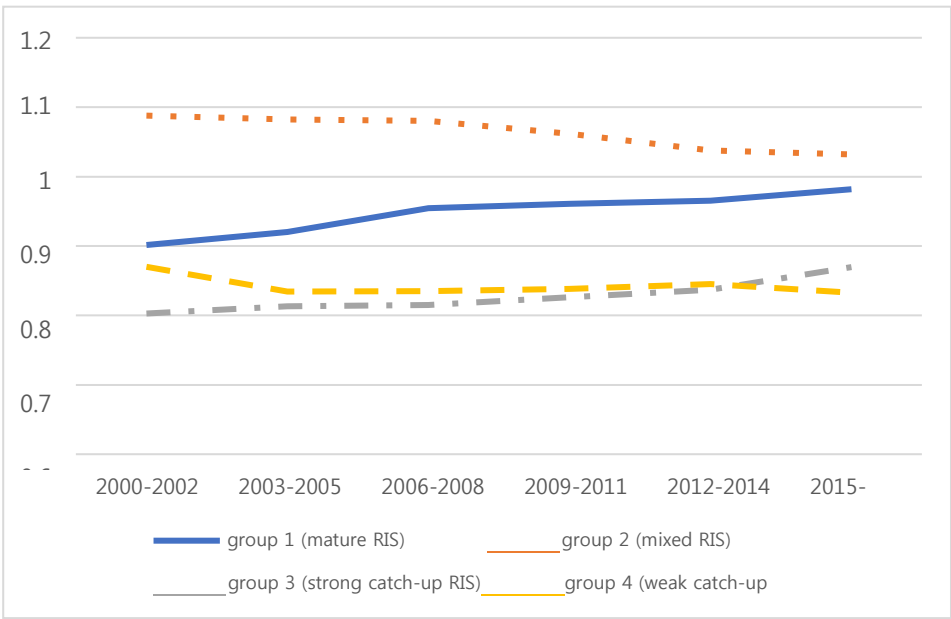
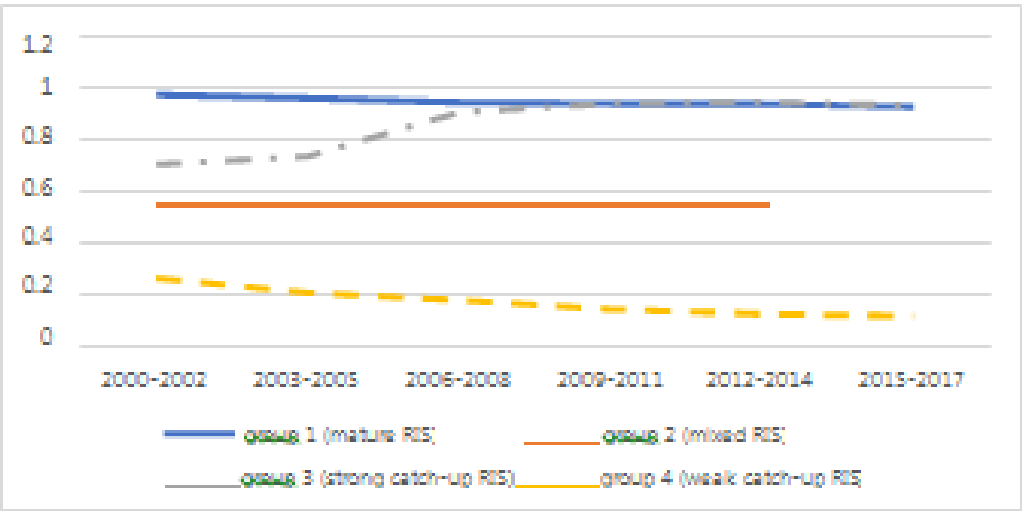
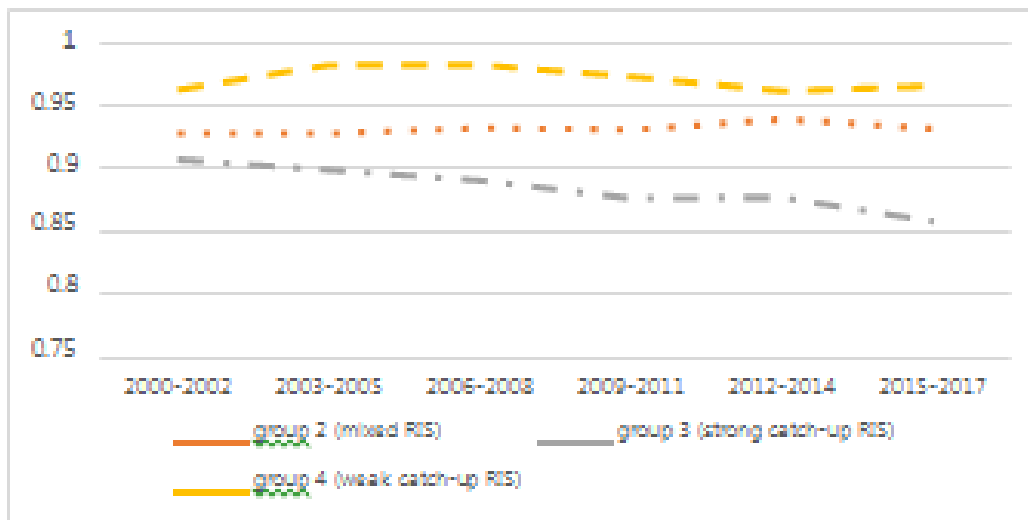


Figure 2B Trends of Local ownership of knowledge by group



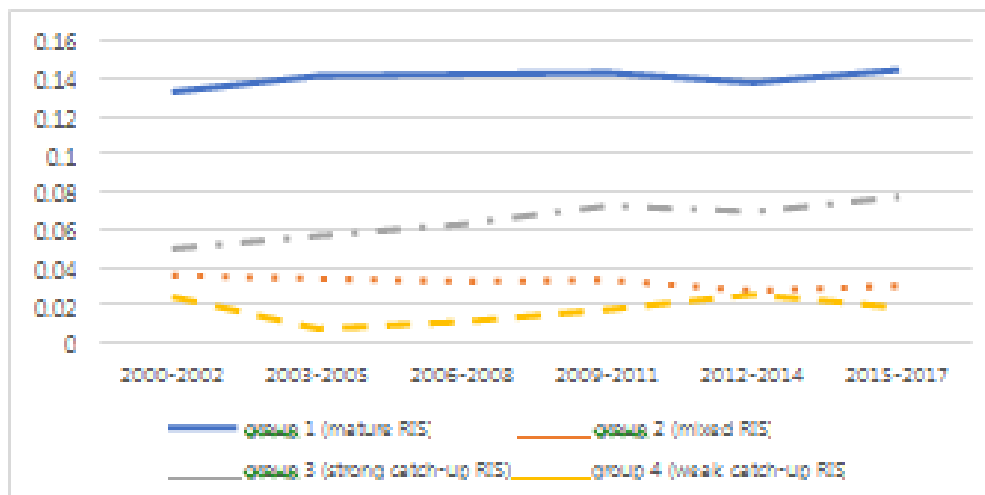
Source: Author's calculation

Figure 2C Trends of International Sourcing by group



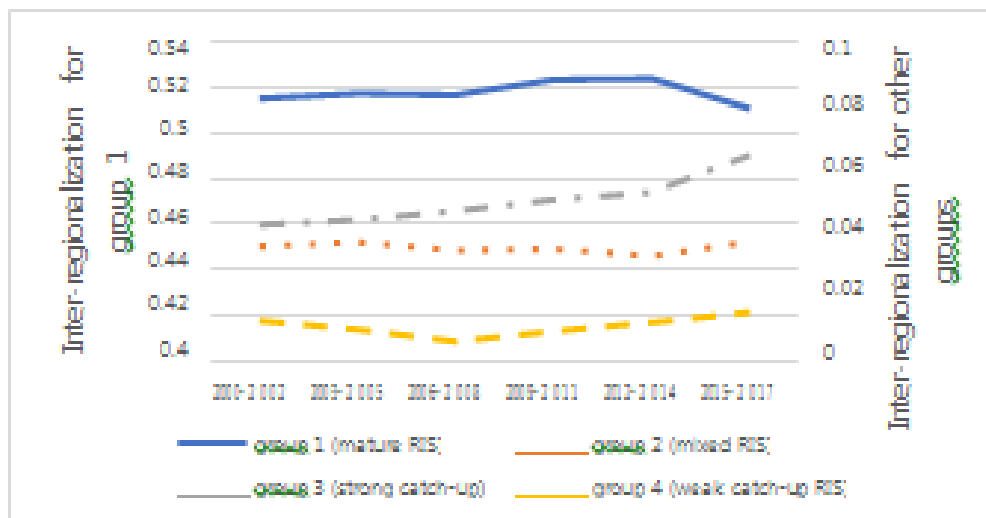
Source: Author's calculation

Figure 2D Trends of Intra-regional Sourcing by group



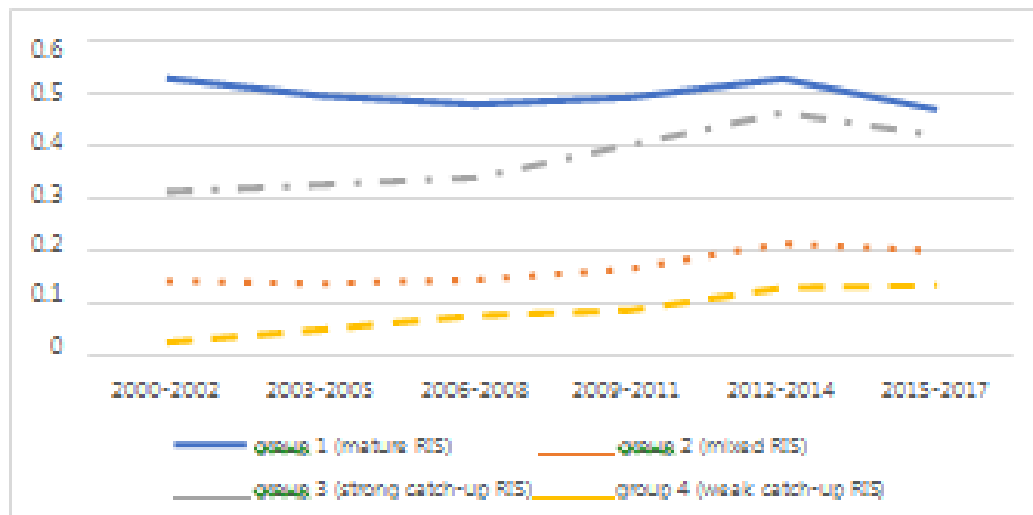
Source: Author's calculation

Figure 2E Trends of Inter-regional Sourcing by group



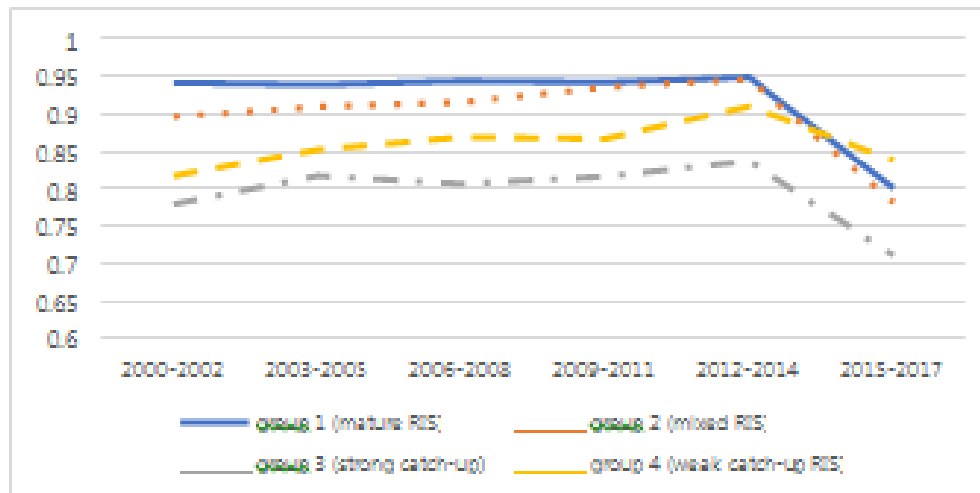
Source: Author's calculation

Figure 2F Trends of Technological diversification by group



Source: Author's calculation

Figure 2G Trends of Knowledge decentralization by group



Source: Author's calculation

Table 2. Results of the Cluster Analysis: Using 7 RIS variables (level of dissimilarity : 0.449)

	2000-2008	2009-2017
Group 1	Silicon Valley, Boston Area, Austin,Houston, Tokyo, Osaka	Silicon Valley, Boston Area, Austin,Houston, Tokyo, Osaka
Group 2	A: Paris, Berlin, Milan, Stockholm,Tel Aviv, London, Cambridge, B: Mexico City, Santiago, Sao Paulo,Johannesburg	A: Paris, Berlin, Milan, Stockholm, Tel Aviv, London, Cambridge, Munich B: Mexico City, Santiago, Sao Paulo,Johannesburg, Hong Kong, Moscow, Beijing, Shanghai
Group 3	Taipei, Seoul, Gyeonggi-do, Daejeon,Munich	Taipei, Seoul, Gyeonggi-do, Daejeon,Shenzhen
Group 4	Penang, New Delhi, Bangalore, Hong Kong, Moscow, Shanghai, Beijing, Shenzhen	Penang, New Delhi, Bangalore

Linking the RIS groups to economic growth

Now, we turn to conduct growth regressions to link the several varieties of RIS to economic growth measured by the growth rates of per capita GDP (GRDP). Equation (1) is a model for the regression analysis.

$$y_{it} = \alpha + \beta pcgdp_{it} + \gamma \{Group_{xit}\}_{x=1}^3 + \delta X_{it} + u_i + u_{it} \quad (1),$$

where y_{it} is a dependent variable, representing the growth rate of per capita GRDP in 2015 PPP based US dollars for region i at time t , and $pcgdp_{it}$ refers to the logarithm of per capita GRDP (USD, 2015 constant PPP) at the initial year of each period for region i at time t . $Group_{it}$ represents the dummy variables representing several RIS groups. Each of the four dummies represent each of the four groups (1, 2, 3, and 4), with each representing the long cycle and high local ownership RIS (large, mature RIS), longer cycle and medium local ownership RIS (mixed RIS), short cycle and high local ownership RIS (strong catch-up), and short cycle and low local ownership (weak catch-up). In actual regressions, the first group serves as a benchmark and thus is not inserted in regression models, and thus there are only three group dummies: $Group_{1it}$, $Group_{2it}$, and $Group_{3it}$, stands for mixed RIS, strong catch-up RIS, and weak catch-up RIS group, respectively. If a region (i) belongs to a certain group at time t , then $Group_{xit}$ equals 1; otherwise, 0. X_{it} is a group of control variables, including population growth and average intellectual capital represented by patents counts per 1,000 person, u_i stands for the region-specific error term, and u_{it} represents idiosyncratic component.

For proper panel data estimation, we need more sub-period than just two in Table 2. So, now the regressions use the data values over the five sub-periods with each of 3 or 4 year length: 2001-4, 2004-7, 2007-2010, and 2010-2013, and 2013 -2017. Each city change its type over time according to the cluster analysis for each of the five sub-periods. Actually, the cluster analysis for each period does not necessarily produce the same results as the recent 9 year result. But, it still generate the same four major groups identified in Table 2, plus some transitory groups which affiliate some city/regions only temporarily or during the first and second sub-periods. Transitory group 1 contains two Japanese cities of Osaka and Tokyo for the first and second sub-period only, and Transitory group 2 includes Johannesburg, Mexico City, Santiago, and Sao Paulo for the first sub period only. So, one set of the regressions use a total of 6 RIS dummy variables, which takes 0 or 1 values for each city depending up the city's grouping in each sub-period. To show robust over the impacts of these transitory grouping of several cities, the other set of regressions use the four dummies only by merging transitory group 1 into the large mature group, and by merging transitory group 2 into a weak catch-up group which is their affiliation from the second period on.

The first and second columns of Table 4 presents the results using the 4 group classification, and thus 3 dummies and one benchmark group. The third and fourth columns show the results for changing RIS affiliations of each city over time, using a total of 5 dummies, including the 3 main dummies and 2 transitory dummies. To show robustness, Table 4 present both results, each for both GMM and LSDV, and the descriptive statistics are available in Appendix Table 2 for the whole and group samples. All the results from the LSDV and GMM estimation are consistent in that the initial GDP per capital is minus and significant, the number of patents per 1,000 person is plus and significant, and population growth is plus and significant except in one model.

Now, the coefficients of RIS group dummy variables all show consistently a positive and significant sign, which means that this grouping is meaningful and that the three RIS groups achieve a faster economic growth than the large, mature RIS group taken as a reference group. The negative coefficient of per capita income corresponds to convergence, and these positive RIS coefficient implies economic catching up, especially by emerging country cities belonging to the two catch-up RIS. The coefficients of weak catch-up group look a bit bigger than those of other groups but the differences are not robustly significant⁹.

Both groups of strong and weak catch-up RIS grow faster than mature RIS, and they have the common technological specialization into short CTT. This part is similar with the result in NIS analysis (Lee et al., 2021). However, we come across somewhat new and different findings.

Compared with the NIS analysis, we find two patterns of catching-up with short CTT specialization. The first pattern is specializing in short cycle technologies with weak indigenous knowledge (Group 4), and the second pattern is specializing in short cycle technologies with strong indigenous knowledge (Group 3). The first pattern corresponds to low income level; the second pattern corresponds to a higher income level than the first pattern. This difference implies that for the sustainable growth to reach a high income status, regions eventually need to increase the contribution of indigenous knowledge, decrease the reliance on foreign knowledge, and increase the local or national knowledge bases.

Table 3 Average values of RIS variables by group: average for 2013 to 2017

2013-2017	Regions/ Cities	Intra- regional sourcing	Inter- regional sourcing	Inter- National sourcing	Local ownership, knowledge	Knowledge decentrali- zation	Tech. diversifi- cation	Relative cycle time	per capita GRDP (USD, 2015 PPP-based)	Growth of per capita GRDP (%)
Group 1 (Large, Mature RIS)	Silicon Valley, Boston Area, Austin, Houston, Tokyo, Osaka	0.14	0.52	0.34	0.94	0.86	0.49	0.98	84592.68	2.27
Group 2 (Mixed RIS)	Total 16 cities in this group	0.03	0.04	0.94	0.57	0.85	0.21	1.03	51658.43	4.44
	[sub-group A] Paris, London, Milan, Cambridge, Stockholm, Munich, Berlin, Hong Kong, Tel Aviv	0.03	0.06	0.91	0.60	0.88	0.24	1.01	67599.80	2.95
	[sub-group B] Moscow, Mexico City, Beijing, Shanghai, Sao Paulo, Santiago, Johannesburg	0.03	0.01	0.96	0.55	0.81	0.17	1.06	31162.38	6.36
Group 3 (Weak Catchup RIS)	Taipei, Seoul, Shenzhen, Gyeonggi- do, Daejeon	0.07	0.06	0.87	0.94	0.76	0.44	0.86	43748.19	5.33
Group 4 (Strong Catchup RIS)	Penang, New Delhi, Bangalore	0.02	0.01	0.97	0.13	0.87	0.14	0.84	20173.93	10.36
Average		0.06	0.13	0.81	0.66	0.84	0.31	0.96	55964.13	4.72

Table 4 Linking RIS to economic growth: Regression results

	LSDV (4 groups)	GMM (4 groups)	LSDV (6 groups)	GMM (6 groups)
log(initial per capita GRDP)	-0.00259*** (0.000901)	-0.00600 (-0.26)	-0.00242** (0.00111)	-0.0296** (-2.02)
No. of patents/1000	0.00754* (0.00386)	0.0188*** (2.96)	0.00741* (0.00425)	0.0185*** (4.76)
population growth	0.952*** (0.279)	0.346 (0.19)	0.936*** (0.290)	1.024** (2.38)
mixed RIS	0.0446*** (0.00623)	0.0704** (2.50)	0.0443*** (0.00758)	0.0422** (1.97)
strong catch-up RIS	0.0432*** (0.00719)	0.0529* (1.85)	0.0434*** (0.00812)	0.0331** (1.97)
weak catch-up	0.0937***	0.101**	0.0952***	0.0575**

	LSDV (4 groups)	GMM (4 groups)	LSDV (6 groups)	GMM (6 groups)
RIS	(0.0139)	(2.30)	(0.0157)	(2.55)
Transitory group 1			-0.000967 (0.00816)	0 (.)
Transitory group 2			0.0801*** (0.0113)	0 (.)
Constant		0.0307		0.296*
		(0.12)		(1.87)
N	150	150	150	150
Hansen		0.353		0.351
no. of cities		30		30
AR(2)		0.590		0.505
adj. R ²	0.734		0.731	
Notes: Dependent variable is the average growth rate of per capita GRDP of each region. Period dummies are included in all estimations. Large mature RIS group is used as a benchmark and is thus not represented by a separate dummy.				

5. Pathways for upgrading and catching up

The preceding section focuses on typologies of RIS and their linkage to economic growth. This section focuses on the pathways for upgrading from one type to other types.

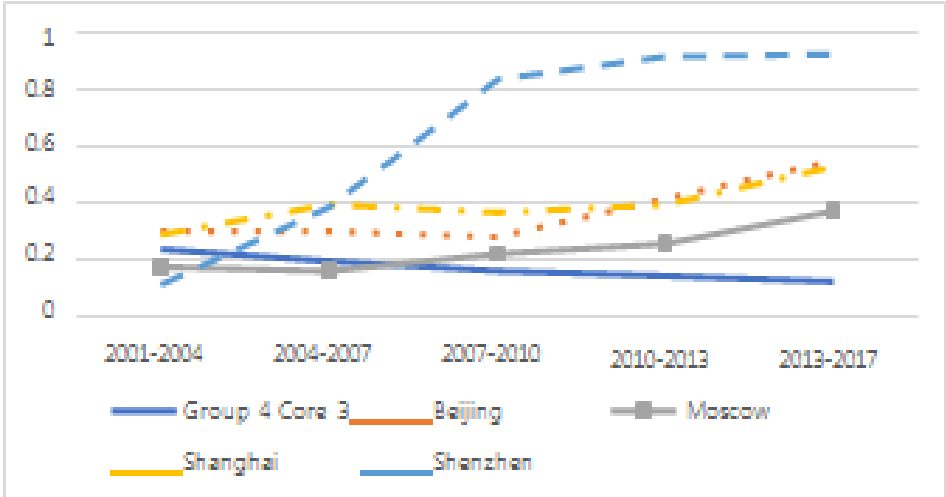
Two pathways for upgrading

As mentioned in the preceding section, several cities changed their RIS types over time (Table 2). We pay attention to two patterns of upgrading between the RIS groups. The first one is a move from weak catch-up RIS (Group 4) to strong catch-up RIS (Group 3), and the second one is a move from a weak catch-up RIS (Group 4) to the mixed group RIS (Group 2). The first pattern includes Shenzhen, whereas the second pattern includes Beijing, Shanghai, and Moscow (the names of these cities are all marked as bold in Table 2B), besides the special case of Hong Kong which used to be a city state.

If we compare Shenzhen to the core three cities (Bangalore, Penang, and New Delhi) in Group 4 (weak catch-up) that remained in this group for the whole period, the main differentiating factor is the different trends in local ownership, followed by inter-national sourcing of knowledge, diversification and decentralization. Figure 3 shows these differences. The degree of local ownership in Shenzhen increased very fast, from less than 20% to close to 90%, whereas the average value of the local ownership for the core three cities in Group 4 remained below 20% for decades (Figure 3A). In Shenzhen, the inter-national sourcing of knowledge decreased from 97% to 93%, but the corresponding

figures for the three cities did not decrease much or stayed around the level of 97% (Figure 3B). Its level of decentralization remained much lower than the average of Group 4, reflecting the rise of big businesses in Shenzhen (Figure 3G). By contrast, we see no differentiating trend in CTT. The average CTT of Shenzhen remained shorter than the compared group, with some rather increasing trend to get close to the level of Group 4's average (Figure 3C).

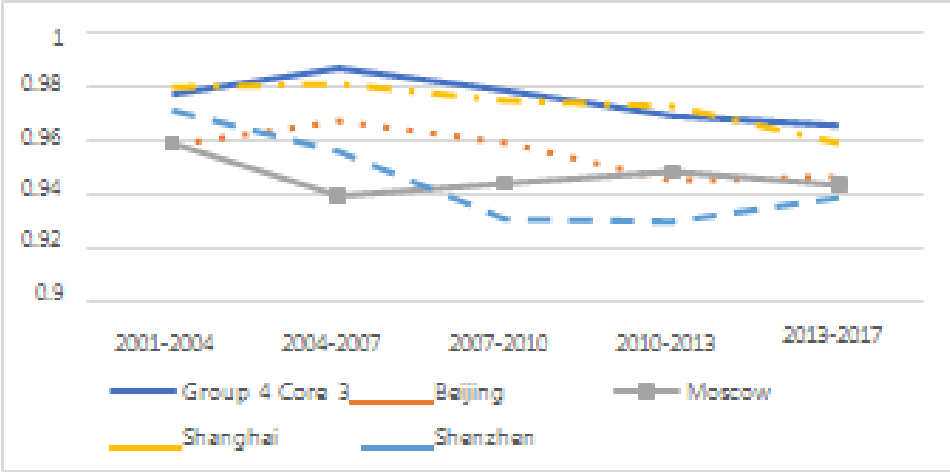
Figure 3A Local ownership of knowledge



Source: Author's calculation

Note: Core 3 include Bangalore, New Delhi, and Penang

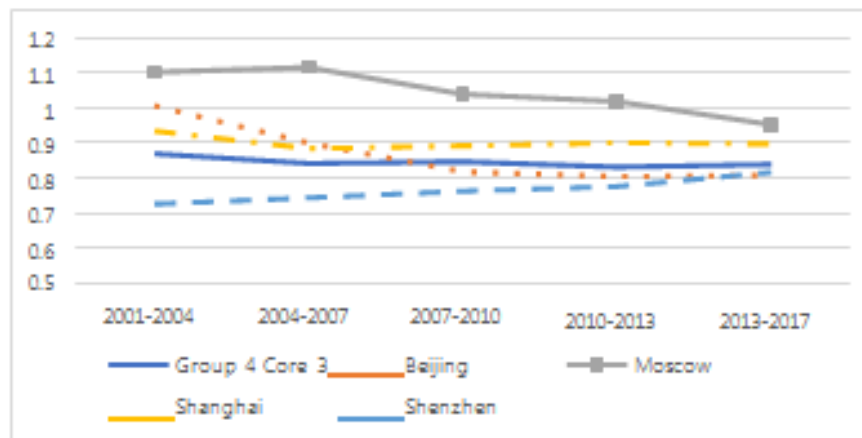
Figure 3B International sourcing



Source: Author's calculation

Note: Core 3 include Bangalore, New Delhi, and Penang

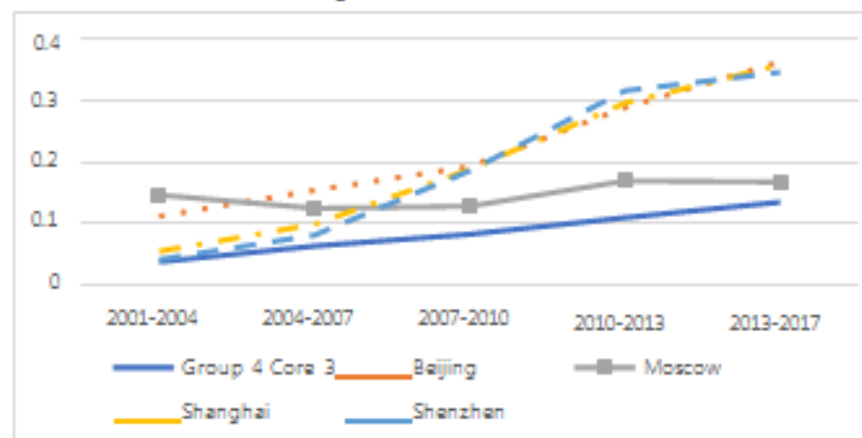
Figure 3C Relative cycle time



Source: Author's calculation

Note: Core 3 include Bangalore, New Delhi, and Penang

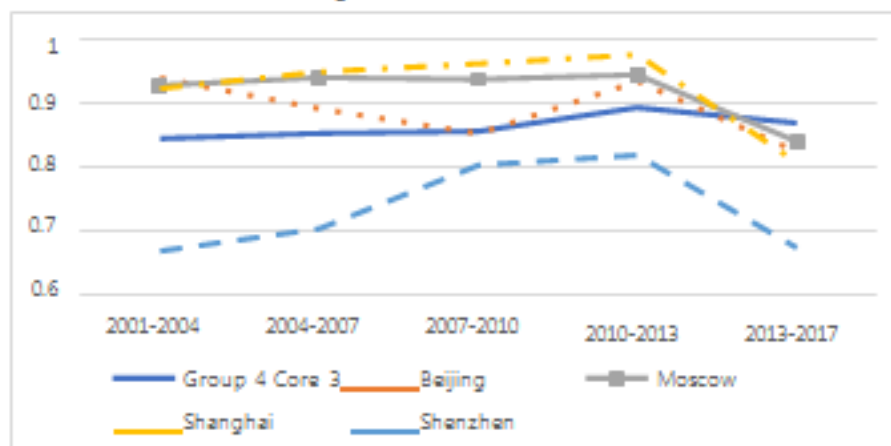
Figure 3D Diversification



Source: Author's calculation

Note: Core 3 include Bangalore, New Delhi, and Penang

Figure 3E Decentralization



Source: Author's calculation

Note: Core 3 include Bangalore, New Delhi, and Penang

For the cases of upgrading from weak catch-up (Group 4) to the mixed group (Group 2), the differentiating factors are again local ownership (increasing), followed by inter-national sourcing of knowledge (decreasing) and diversification (increasing). We see no differentiating trend in CTT. The values of CTT of the three upgrading cities remained above or similar to the average CTT of Group 4. Although Moscow and Beijing showed some decreasing trend, Shanghai showed no change at all, remaining similar to the average of Group 4.

In sum, the two pathways for upgrading feature in common the trend of increasing local ownership and decreasing reliance on foreign knowledge (internationalization). CTT does not show any clear-cut trend. This implies importantly that increasing local sourcing and decreasing foreign sourcing of knowledge should be the most important factors for upgrading, whereas short CTT specialization does not automatically guarantee this to happen. A right combination of short CTT and local ownership is required, and that is the main defining characteristics of the strong catch-up group.

Decentralization versus centralization for catch-up

Another issue in the pathways for upgrading is whether a latecomer city should pursue decentralized way of innovation distribution or centralization into the hands of a few number of big businesses. If we look at the trend of decentralization in Figure 3E, we note that the strong catch-up group corresponds to the lowest degree of decentralization (or highest centralization), and does not show a clear-cut trend of further decentralization. By contrast, Groups 2 and 4 present a noticeable decentralizing trend. This divergence implies different modes of upgrading and catching up.

Given that Group 3 include cities in South Korea and Taiwan as well as Shenzhen, it is unsurprising that these cities represent upgrading led by big businesses that are also locally owned matched by the decreasing trend of inter-national sourcing of knowledge. Although Beijing, Shanghai, and Moscow has recently joined Group 2, they have also most recently increased the degree of centralization (Figure 3E), in parallel with increasing local ownership during the most recent period and rapid diversification. If such trends continue in the future, these three cities can be expected to move beyond the current Group (2) to join Group 3 (strong catch-up).

Mixed RIS as another pathway

One remaining issue may be a viability of the mixed RIS as a possible model for catching up by latecomer cities. The average values of RIS variables for cities from emerging economies in this group is quite similar to those for cities in the same group but from advanced economies. This interesting homogeneity in RIS raises an important question of why then per capita income levels remain so different between these two sub-groups, for instance, \$32,749 vs. \$69,561 (Table 3). Their income level (\$32,749) is also much lower than the average of the strong catch-up group (\$43,748). The persistent difference in income level despite the similar RIS values implies that such a difference may not be sufficiently explained by region-level factors. One answer may be the role of national-level (or NIS) factors affecting performance of cities within a nation in addition to other regional variables not considered here. We will answer this question in future studies, where we will explore in detail how the interaction of RIS and NIS variables affect the performance of cities.

Another possibility is that the current states of cities from emerging world is not an end-state equilibrium but only a transitory state. Some of them may increase further the local ownership from the current values of 50% or 60% or so to more than 80% or close to the level of strong catch-up group. Shenzhen is an example of upgrading to Group 3 (strong catch-up group) via this pathway. The degree of local ownership used to be less than 40% in the mid-2000s but reached more than 90% by the mid-2010s.

6. Summary and concluding remarks

We attempt to identify quantitatively the characteristics and types of RIS of regions and cities in emerging economies in comparison to those in advanced economies. We adopt and modify the Schumpeterian framework and methodology of innovation systems, which was originally developed at national level. We measure seven variables expressing the diverse aspects of a region's innovation systems, using the citation data of the US patents filed by 30 regions and cities around the world.

Among the seven RIS variables, four are newly developed, namely, intra-regional, inter-regional, and inter-national sourcing of knowledge and local ownership of innovation. The other three are used in the recent literature, and they are CTT, technological diversification, and decentralization. The cluster analysis of these variables enable us to identify four major types of RIS around the world and link them to regional economic performance.

The four types are, in the descending order of their per capita income levels, as follow: large, mature RIS characterized by a combination of long cycle technology specialization and high local ownership (Group 1), mixed RIS characterized by a long cycle and low local ownership (Group 2), “strong catch-up” characterized by short cycle and high local ownership (Group 3), and “weak catch-up” characterized by short cycle and low local ownership (Group 4). Consistent with the findings from the NIS literature, Group 1 tends to boast equally high values in all of the six variables and the lowest value in inter-national sourcing. In particular, it has higher values in inter-regional sourcing, which reflect the size of national economy the cities belong to. In sharp contrast, Group 4 is in the opposite spectrum tend to show low values in all of the six variables and the highest value in inter- national sourcing of knowledge, which is expected from an immature or peripheral RIS with lack of indigenous knowledge base and embeddedness. Growth regressions confirm that Groups, 2, 3, and 4 correspond to faster rates of growth compared with the benchmark group, Group 1.

An interesting and contributing finding is that Groups 3 and 4 include mostly the regions in emerging world and thus similarly specialize in the same short CTT-based sectors. However, they show somewhat different records of economic catch-up and income levels. The key differentiating variable is the degree of local ownership of knowledge and innovation, which can be a basis for increasing domestic sourcing of knowledge and sustained catching up to a high income level. Several cities, such as Shenzhen, Moscow, Beijing, and Shanghai, which experienced the pathways of upgrading from Group 4 in the earlier period to either Group 3 or 2 in later periods, also show a rapid or steady increase of local ownership, followed by increasing domestic sourcing and decreasing inter- national sourcing.

Another important variable is decentralization, which is associated with the fact that the level of decentralization in the strong catch-up group is lower than that in the weak catch-up group, whereas Group 1 boasts the highest level of decentralization associated with more dispersed and diverse sources of innovation. Such a pattern in Group 3 implies that catching up has been led by a small number of big businesses rather than a large number of SMEs. This pattern is consistent with the experiences of South Korea, Taiwan, and mainland China, which all generate some of the Global 500 Fortune class firms. Several cities experiencing upgrading, like Moscow, Beijing, and Shanghai, also

show a decreasing trend of decentralization. This point of catching up led by big businesses is actually consistent with the finding from the NIS literature, like Lee (2013) and Lee et al. (2021). It is called a detour path, meaning that they will be eventually more decentralized at later stage of development.

Overall, some of the findings are consistent with those of NIS literature, but others are new and distinctive. One source of difference between the NIS and RIS analyses for emerging economies is that although some cities and regions in our sample are located in the middle-income trap countries, their own income level is already quite high compared with the national average of the affiliated nations.

This study has a number of contributions. First, this research makes a methodological contribution of developing quantifiable measures of RIS using a homogenous set of data (patent-citations based indices). This is one of the first quantitative RIS analysis using patent data and covering many and diverse regions across worlds. Second, it contributes to the field by identifying characteristics of RIS of catching-up regions, different from mature cities in advanced economies and linking them to economic growth. Third, it identifies a common mechanism of RIS upgrading, which is led by locally owned big businesses exploring more of domestic sourcing of knowledge while reducing reliance on foreign knowledge. The findings can be useful to derive policy implications for latecomer regions in their effort to catch up with advanced regions.

However, several limitations can be noted. First, there is a possibility of ambiguity or softness of the borders of RIS because the borders of RIS do not fit to that of the administrative districts of the region. We only include the regions already achieving some innovation output or integrated into certain parts of the global value chain; thus, this study is limited in deriving implications for regions starting the early stage of innovation and economic growth. Besides, we do not use much of other, especially tacit knowledge, indicators of regions, such as industry and trade structure, labor market institutions, and government-business relations.

Nevertheless, this study shows a new and useful way of measuring and comparing RIS around the world. Analyses of this kind are still at early stage of progress. The current stage is mostly for generating more stylized facts and identifying new regularities. A more rigorous analysis for further generality or causality will be done in future studies. Other topics for future studies are the role of national institutions and other variables on growth of cities and their RIS and the manner in which the interaction between the RIS and NIS variables affect the performance of a region.

Appendix

Appendix 1: Additional RIS variables

First, technological diversification refers to the number of diverse fields of technologies a region/nation has filed a patent for and can be defined as follows (Lee et al. 2021; Lee, 2013):

$$Diversification_i = \frac{N_i}{\text{total number of classes}}.$$

where N_i refers to the total number of technological classes that patents from region i are registered (i.e., in how many diverse fields a region has filed the patents). The total number of classes in the patent systems can be determined at several levels, such as three or four digits. The number in the US patent classification system was 473 classes at the three-digit level in 2019.

Second, decentralization or concentration of innovation measures the degree of even or uneven distribution of innovators (patent assignees and legal owners of patents), i.e., whether innovation is conducted by a large number of firms or dominated by a few large firms. Thus, Herschman– Herfindahl index (HHI) can be measured with the following formula (Lee, 2013):

$$HHI_{xt} = \sum_{i \in I_x} \left(\frac{N_{it}}{N_{xt}^*} \right)^2,$$

where I_x is the set of assignees, N_{it} is the number of patents filed by assignee i in year t , and N_{xt}^* is the total number of patents filed by region x in year t , excluding unassigned patents. We then use the formula of $(1 - HHI_{xt})$ to define the variable of the decentralization of innovation over assignees in region x in time t (Lee et al., 2021).

Third, the variable of cycle time of technologies (CTT) is first proposed in Jaffe and Trajtenberg (2002) and used in Lee (2013). Its definition is as follows:

Cycle time of technologies

$$= (\text{Grant year of patent } i) - (\text{grant year of patent cited in patent } i)$$

This absolute value of CCT keeps increasing over time, so defining whether the technology is changing rapidly or slowly is difficult. In this sense, this value is normalized around 1, which is named as relative (or normalized) CTT. The formula for relative CTT is

$$\text{Relative cycle time of technologies} = \frac{CTT_i}{\text{Average value of CTT in year } t}$$

If the relative CTT is smaller than 1, the region specializes in short-cycle technologies; otherwise, long-cycle technologies.

Appendix 2: Definition of the regions in the US

In the analysis, Boston–Cambridge area (hereafter referred to as Boston), Silicon Valley, Houston area, and Austin area are defined as follows. In the US, the minimum administrative level for regional data is county level, which often include cities inside it. Hence, we define the above areas as a sum of several related counties or a county itself that include cities. The Boston area includes two counties, Middlesex county where Boston city belongs to and Suffolk county where Cambridge city and Somerville belong to. The Houston area is basically the Harris county, and the Austin area is the Travis county. In these cases, each county includes the cities within its administrative boundary.

Silicon Valley started with San Jose in Santa Clara county as its core area. The region expanded to include several neighboring counties (Mann & Luo 2010). According to Guzman and Stern (2015), Silicon Valley comprises as many as 35 cities belonging to several counties. There is no formal definition, and Silicon Valley is broadly considered to include areas surrounding San Francisco Bay. In our study, we consider Silicon Valley as the four counties surrounding the bay, which are Alameda county, San Francisco county, San Mateo county, and Santa Clara county.

Appendix 3: Sources of economic indicators

The biggest source for the data on gross regional domestic product (GRDP) and population are from the data set called Regional Economy in the OECD database. Data on the purchasing power parity are from World Bank. In the case such data are unavailable for some regions, we resort to the sites of the government of each country or region. Specific details follow.

In case of the regions in the US, we use county-level data available from the US Bureau of Economic Analysis. For Cambridge in the UK, data on its GRDP and population are from the official website of the government and its Office for National Statistics:

<https://www.ons.gov.uk/economy/grossdomesticproductgdp/data/sets/regionalgrossdomesticproductlocalauthorities>;
<https://www.ons.gov.uk/economy/grossdomesticproductgdp/data/sets/regionalgrossdomesticproductlocalauthorities>.

For data on Osaka and Tokyo in Japan, the System of Social and Demographic Statistics in the Statistics of Japan provides prefecture level for population for

each region in Japan. As OECD provides the GRDP data from 2001 to 2017 for the two regions in Japan, we use the growth rate of GRDP from the Prefectural Economy in Cabinet Office Policy to re-calculate each region's GRDP in 2000. Regarding the population data for the regions in Korea such as Gyeonggi-do, Seoul, and Daejeon, we use Korean Statistical Information Service: <https://kosis.kr/index/index.do#none>.

In China, each regional government provides its own statistical yearbook. OECD provides the GRDP and population data for Beijing and Shanghai. For Shenzhen, the necessary data of GRDP and population are from the Shenzhen Statistical Yearbook. The Census and Statistics Department of the Government of the Hong Kong Special Administrative Region provides GRDP and population data for Hong Kong. In this study, Taipei region includes New Taipei and Taipei City. The statistics department of Taiwan does not provide the gross regional domestic product but provides regional per capita income and population.

In this case and others, including Bangalore, we estimate per capita GRDP by multiplying the ratio of per capita income of a region to national average by per capita GDP of a country to which a city belong. GRDP data for Bangalore are not provided, but per capita income data are provided by Directorate of Economics and Statistics in the Government of Karnataka. Data on per capita income from 2000 to 2016 are from State and District Domestic Product of Karnataka 2017–2018 and data on regional per capita income from 2017 to 2018 are from the Economic Survey of Karnataka 2018– 2019 and 2019–2020. The data on population, GRDP, and per capita GRDP in 2017 are from District Domestic Product of Karnataka 2016–2017 provided by Directorate of Economics and Statistics. GRDP and population data for New Delhi are from Economic Survey of Delhi.

In Malaysia, National Accounts of Department of Statistics provides the gross regional domestic product and population of Penang. Mexico City data on GDP and population are from National Institute of Statistic and Geography (Instituto Nacional de Estadística y Geografía, INEGI). They provide GRDP in 2013-based price, so we transform GRDP in 2015-based USD using GDP deflator and PPP provided by World Bank. Brazilian Institute of Geography and Statistics provides GRDP and population for Sao Paulo (<https://sidra.ibge.gov.br/home/pmc/brasil>). In case of Santiago, we consider the Metropolitan of Santiago as Santiago and use data of GRDP and population provided from Statistical Bulletin in Banco Central Chile. We use GDP and population data for Singapore from World Bank.

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Appendix Table 1 Average Values from 2013 to 2017 (order by per capita GRDP)

	Average growth rate of per capita GRDP	Average per capita GRDP	population	patents	total patents per 10,000
Paris	3.02	120,803.05	12,775,109	584.2	0.29
Silicon Valley	5.74	118,983.42	5,155,804	22,779.0	11.39
Boston Area	1.89	109,832.16	2,366,265	4,066.8	2.03
Austin	4.46	81,342.80	1,177,602	2,386.4	1.19
Houston	-0.59	80,899.69	4,529,792	2,070.4	1.04
Tokyo	0.52	74,242.84	9,272,390	11,446.2	5.72
London	3.59	71,311.04	12,084,662	390.8	0.20
Milan	0.92	70,127.41	4,905,173	253.6	0.13
Cambridge	2.77	69,436.76	372,801	432.8	0.22
Taipei	3.62	68,817.73	6,666,178	3,972.8	1.99
Stockholm	2.86	67,727.17	2,185,874	294.8	0.15
Munich	3.62	57,396.88	2,806,039	787.0	0.39
Hong Kong	4.78	56,203.47	7,312,740	625.0	0.31
Tel Aviv	1.50	49,168.32	1,351,360	402.0	0.20
Moscow	6.72	47,320.05	12,199,240	261.0	0.13
Berlin	3.52	46,224.14	5,073,591	500.6	0.25
Seoul	4.44	43,665.01	9,903,047	4,681.6	2.34
Mexico City	7.55	42,521.07	8,853,550	42.4	0.02
Osaka	1.62	42,255.16	2,692,969	4,060.2	2.03
Shenzhen	7.82	42,098.20	11,444,640	2,296.4	1.15
Gyeonggi-do	6.32	36,045.33	12,443,481	9,302.2	4.65
Penang	6.90	29,587.08	1,700,120	98.6	0.05
Beijing	7.82	28,452.85	21,561,000	3,085.4	1.54
Daejeon	4.46	28,114.70	1,540,854	1,578.0	0.79
Shanghai	8.07	27,699.63	24,188,260	1,420.8	0.71
Sao Paulo	4.06	27,213.24	11,966,137	79.2	0.04
Santiago	5.53	23,286.69	7,228,440	43.6	0.02
Johannesburg	4.76	21,643.15	4,913,514	31.6	0.02
New Delhi	9.34	15,573.05	18,520,200	153.0	0.08
Bangalore	14.84	15,361.66	10,157,455	1,103.6	0.55
Average	4.75	53778.46	7911609.57	2641.00	1.32

Appendix Table 2: Descriptive Statistics

<i>All regions for whole period</i>	mean	standard deviation	min	max
growth rate of per capita GRDP	0.054	0.079	-0.385	1.090
log of initial per capita GRDP	10.351	0.863	7.310	11.646
patent counts per 1000	0.338	0.654	0.000	4.604
population growth rate	0.013	0.013	-0.037	0.059
N	150			
<i>Mature RIS for whole period</i>				
growth rate of per capita GRDP	0.014	0.020	-0.024	0.057
log of initial per capita GRDP	11.245	0.263	10.605	11.568
patent counts per 1000	1.236	1.099	0.255	4.415
population growth rate	0.012	0.009	-0.003	0.028
N	26			
<i>Mixed RIS for whole period</i>				
growth rate of per capita GRDP	0.046	0.028	-0.011	0.130
log of initial per capita GRDP	10.517	0.608	9.230	11.646
patent counts per 1000	0.104	0.192	0.001	1.161
population growth rate	0.010	0.009	-0.003	0.034
N	56			
<i>Strong Catch-up RIS for whole period</i>				
growth rate of per capita GRDP	0.051	0.026	0.003	0.129
log of initial per capita GRDP	10.418	0.410	9.742	11.047
patent counts per 1000	0.377	0.234	0.052	1.025
population growth rate	0.010	0.012	-0.005	0.045
N	23			
<i>Weak Catchup RIS for whole period</i>				
growth rate of per capita GRDP	0.111	0.078	-0.062	0.326
log of initial per capita GRDP	9.488	0.881	7.310	10.998
patent counts per 1000	0.053	0.147	0.002	0.896
population growth rate	0.023	0.014	0.003	0.052
N	37			

Notes

- ¹ It refers to the degree of national-level self-citation after normalization and is thus designed to be free from the size effect (i.e., a big country has a high localization ratio). If the degree of localization is large, then the domestic diffusion of knowledge is high, but the share of foreign patents in the citation is low.
- ² Given that the three measures are summed up to be one, for the purpose of the analysis, normalization needed in national-level analysis using the concept of control patents proposed to control the size effect is unnecessary (Jaffe et al., 1993).
- ³ Our analysis of RIS omits the originality variable, which is shown to be less significant in the literature, such as Lee (2013, Chapter 3), thus suggesting that originality may not have a significant effect to economic growth at least at the catching-up stage. In Kim and Lee (2022), originality also does not play an important role in explaining different speeds of economic catch-up between the three regions.
- ⁴ Technological diversification is measured by the number of technological classes in which a country/region has registered patents divided by the maximum number of three-digit patent classes in the patent classification system (this number was 438 in 2016, and we use this number for every year). Although a Herfindahl-Hirschman index (HHI) is an alternative, this measurement has a more direct and easy-to-interpret meaning and many variations across the country.
- ⁵ In our analysis, we use relative (or normalized) CTT, which is the absolute years of the CTT divided by the average CTT of all patents granted in the same year. We use the average values of the relative CTT of all patents assigned to each country for analysis.
- ⁶ Lee et al. (2021) categorize the NIS in four groups i.e., balanced and mature NIS, balanced and medium-cycle NIS, imbalanced, short-cycle, and catching-up NIS, and imbalanced, long-cycle, and trapped NIS. Among these four, the two imbalanced NIS groups are relevant for emerging economies. In imbalanced and short-cycle NIS, knowledge creation is highly localized, technologies are highly diversified, and economies in this group specialize in short-cycle technologies, and this group tends to correspond to a faster catching up compared with imbalanced and long-cycle NIS. The imbalanced and long-cycle NIS group has features of low localization and diversification and specializes in long-cycle technologies. This group includes those countries that face growth slow-down and thus are stuck in the middle-income trap.
- ⁷ The first step is to acquire the patent data files by manually downloading 2,132 separate files. The second step is to decompress the downloaded data and begin parsing the corpus and converting it to SAS data sets. The third step is to use SAS programming to create a program that can parse all documents in the corpus and then catalog the patent numbers for each patent granted since 1976.
- ⁸ For instance, the empirical literature on NIS uses many variables to capture diverse aspects of an economy, ranging from techno-economic to political institutional dimensions and IT-related infrastructure, and even openness and financial systems. Although the broad scope may be a merit, such breadth blurs the boundaries between innovation and other areas of the economy, often leading to NIS groupings that are difficult to interpret. See Lee et al. (2021) for a detailed discussion of this point.
- ⁹ A test using the result reported in the first column shows that the difference is not significant.

Panela in El salvador, towards an emerging sectorial system of innovation and production: ACOPANELA case study

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Abstract

This research explores whether panela artisan entrepreneurs in El Salvador are emerging as a sectoral innovation and production system (SIS), demonstrating enormous resilience in the face of the process of creative destruction unleashed by competition from industrialized sugar. The methodology applied is qualitative, and the results show that: i) in the panela agro- industry, the various components that constitute a SIS are present, in an incipient state, and ii) ACOPANELA has established innovation based on building networking capacities as a competitive advantage, highlighting the dynamic assimilation of technology from the regional center for excellence CIMPA - AGROSAVIA in Colombia. Thus, it is contrasted that, in the Global South, often the most important asset is not knowledge itself given its location in the neo-periphery of the Global Learning Economy, but the establishment of networks with robust actors who possess innovative knowledge in centers of excellence from global value chains such as CIMPA - AGROSAVIA.

Keywords: Innovation; CIMPA; AGROSAVIA; productive system.

1. Introduction

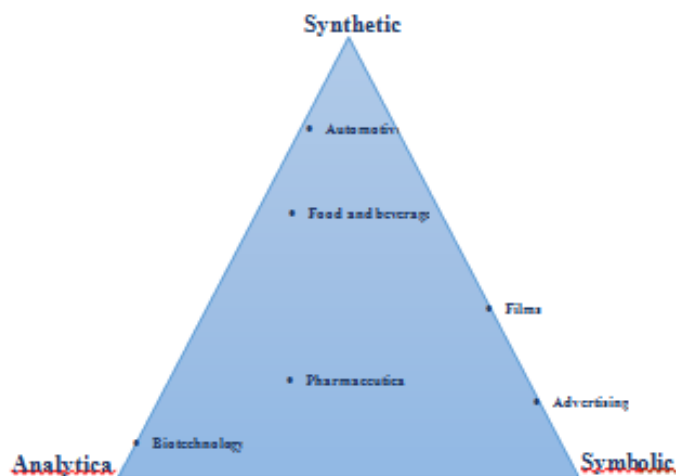
In view of the developments of the Global Learning Economy (Lundvall, 2016), it is pertinent from the Global South, to investigate whether some of its industries are reaching levels of maturity that allow them to apply the approaches of that discipline, in this case, Sectoral Systems of Innovation and Production approach (SIS) of Malerba (2002), already widely used for developing countries (Malerba & Mani, 2009), but rarely to analyze dynamics of small scale rural agro industries like the *panela* in countries like El Salvador on the periphery of the Global South. This sectorial notion of innovation systems is versatile as its borders and level of aggregation can be adjusted to the changing economic and technological realities that are being analyzed (Peraza Castaneda, 2019), however, it must adequately include all the basic components of that system (Malerba, 2004): institutions (rules of the game), actors including their networks and knowledge bases, with emphasis on the latter as they constitute a differential aspect of this notion. In the case of *panela*, the combination of tacit knowledge bases generated during the experiences of generations of families “*paneleras*”, that have participated in the process of emergence and evolution of the Cooperative Association of “*Paneleros*” of El Salvador (ACOPANELA), with the scientific and technological bases of the innovative knowledge for integrating Better Manufacturing Practices and granulated panels, is considered of special relevance. So, this last type of knowledge has been assimilated in this agri-food system located in the Jiboa Valley of El Salvador, mainly from the center of excellence of innovative knowledge on *panela* production in Latin America, in

Colombia: The International Center for *Panela* Improvement (CIMPA, currently part of AGROSAVIA¹).

The institutions under this approach constitute the rules of the game, the routines, common habits, established practices, rules, laws or norms which guide the behavior of the actors that participate in the innovative processes (Edquist, 1997; Nelson & Sampat, 2001). Regarding the actors, heterogeneous agents can be identified that interact through processes of communication, exchange, cooperation and / or competition. The nature of these agents can be both market (other firms in their value chain such as suppliers, customers, even competitors), and non-market (universities, financial organizations, government agencies, local authorities, etc.), that support innovation, technological diffusion, production and commercialization of the goods and services produced by the diversity of firms in the sector, in different ways. Within sectoral systems, these agents are connected through market and non-market relationships. Hence, networks allow access and integration of complementary aspects of knowledge, skills and specialization (Edquist, 1997; Lundvall, 1992; Teubal et al., 1991).

The third essential component of a sectoral innovation and production system is its knowledge base; where the nature of this could be analytical, synthetic, or symbolic (Asheim, 2009). An analytical knowledge base refers to industrial settings in which scientific knowledge is very important; while one of a synthetic nature, to industrial environments where innovation is carried out mainly through the application of existing tacit knowledge or through new combinations of these. A final possibility is a symbolic knowledge base, where the associated knowledge relates to the aesthetic qualities of products, the creation of designs and images, as well as the economic use of various forms of cultural artifacts. The Knowledge Bases, in turn, are related to the dominant learning mode in the sector, which may be: DUI learning (doing, using, interacting) based more on experience and synthetic knowledge (symbolic knowledge also corresponds); or STI (science, technology and innovation) learning based on analytical knowledge generation processes (Jensen et al., 2007). On the other hand, Asheim et al. (2007) state that both the combination of knowledge generated and that used by companies when innovating shows common features among those that belong to the same sector. This reality can be explained by the heterogeneous knowledge needs of the different productive sectors (Fig. 1).

Fig. 1. Knowledge bases and industrial sectors.



Source: Peraza Castaneda (2019) based on Asheim et al. (2007).

An even more disruptive nuance to analyze the structure of an industry from the innovation systems approach consists in understanding the sectoral system of innovation and production (Malerba, 2002) as the union, from the perspective of set theory (Lipschutz, 1991), of various technological innovation systems (TIS) (Markard & Truffer, 2008). This proposal was designed and applied by Andersen (2015) to the case of the sugarcane industry in Brazil from its cultivation to the production of biofuel, and it is applied in the discussion of our results.

In this study, through qualitative methodology, it is verified from an evolutionary perspective whether the small Salvadoran panela rural agroindustry has transcended to be an emerging SIS in the Global South, contrasting the extent to which each of the elements of that approach is present at least in an incipient state. Emphasis is placed on the importance of building networking capacities for innovation as a source of sustainable competitive advantage for a key social economy initiative in the Salvadoran and Central American panela sector, ACOPANELA.

2. Methodology

To carry out this study, a review of the relevant literature was made to contextualize the case of ACOPANELA within the framework of the historical evolution of sugarcane cultivation for the generation of different types of sugars using different technologies for their production, and more specifically of panela in El Salvador, seen as the basis for the emergence of a Sectoral System of Innovation and Production. This review was carried out through documentation searches in: international databases, from journals (Scopus, Web of Knowledge and Google Scholar, Dialnet); agro-industrial statistics (Food and Agriculture Organization-FAO and World Bank) and other types of national documents (Salvadoran Higher Education Organizations). For processing the secondary sources, an analytical- synthetic process was applied, which consists of the dismemberment of a whole, breaking it down into its parts or elements to observe the causes, nature, and effects, and then relate each reaction through the elaboration of a general synthesis of the studied phenomenon; and this is how the state of the art and the part of the results of the research on historical evolution and technical corroboration of the existence of a panela SIS were established.

It is in this context that the results of the case study of the emblematic ACOPANELA- Cooperative Association for Agro-industrial Production, Supply, Marketing and Financing of Paneleros Producers of the Jiboa Valley are presented. They are based on semi-structured interviews conducted with the cooperative's management team between October 2021 and February 2022, in addition to previous ones carried out by one of the authors (Cummings & Cogo, 2012). As a case study, Cummings & Cogo (2012) argue that:

In the Central American regional and national context, ACOPANELA is a "critical case" since it has a "strategic importance in relation to the problem in general" of how to strengthen the productive capacities and competitiveness of small rural agroindustries that of panela (Flyvbjerg, 2004, p.426). The ACOPANELA cooperative offers potentially relevant lessons for innovative strengthening of similar industries with significant traditional knowledge bases that face complex challenges which

require access to exogenous sources of innovative knowledge and resources to overcome them:

The case study in the version presented here is built based on previous descriptions and analyzes carried out on the experience of ACOPANELA in co-evolution with the dynamics of its sectorial and territorial context carried out by Cummings (2007) Cogo (2009), Cummings and Cogo (2012).

Questions regarding the emergence, evolution, and relevance of innovation capabilities and especially linkage and relationship with exogenous actors (networking) were addressed in in-depth interviews with a founding partner, first and current president of ACOPANELA (March 2011), a representative of the IDB-FOMIN office in El Salvador who was one of the main people who supported the development of the initiative from its institutional position (April 2011). These, which were fundamental for the elaboration of the case published by Cummings and Cogo (2012), were complemented by additional interviews with the current president of ACOPANELA, the current manager and the former manager and advisor of the cooperative (February 2022) carried out with the purpose of updating knowledge on the current state of development of the cooperative and deepening understanding of the relationship between ACOPANELA and CIMPA - AGROSAVIA, as the Latin American center of excellence of the panela sectoral innovation system.

The evidence from this set of in-depth interviews was complemented by a diversity of bibliographic sources, from published or unpublished texts, including newspaper articles on relevant activities in the evolution of the cooperative, such as those on the panela tourist route, as well as evaluation reports of the IDB-MIF projects to support ACOPANELA (unpublished) and another on the results of an important visit made by political and technical leaders of ACOPANELA to an international trade fair held in Taiwan.

The case, however, should still be considered exploratory, given the complexity of the object of study: the emergence, evolution, and scope of ACOPANELA's innovation capabilities in the face of its challenges to strengthen its capabilities to have a positive impact on the well-being objective of its cooperative members.

3. Results and discussion

This part is organized into three sections to better present and discuss the findings on the panela SIS in El Salvador: its technological trajectory, status of the SIS for each of its components according to Malerba (2004), and the importance of the construction of networking capabilities for innovation exemplified by the ACOPANELA case study.

3.1. Evolution of the cultivation and processing of sugarcane in El Salvador

Regarding the origins of sugarcane cultivation in El Salvador, it is considered that one of the 63 founders of San Salvador, Sancho de Figueroa was the first to plant sugarcane on one of his properties near Cojutepeque in 1532, later the cultivation would spread in the territories of the then Provinces of San Salvador and San Miguel, as well as the Mayor of Sonsonate. As to the first official statistics of sugar production in trapiche, as well as the elaboration of other derivatives, these date from the mid-nineteenth century. The General Statistics (1858-1861) reflect the existence of sugarcane crops and the production of panelas and sugar in the central and western areas of the country, although the volume of these activities was almost insignificant compared to coffee production (Cañas-Dinarte et al. al., 2009), since the latter was already establishing itself as the first export product to the detriment of indigo (Alvarenga et al., 1994).

The production process at that time was artisanal, being the panela or "tied sweet" made in sugar mills that would be concentrated in the Jiboa Valley area. A hacienda that would become emblematic in the sector called "El Ángel" under the leadership of its owner Rafael Meléndez Quirós in 1862, was restructured to dedicate itself totally to the intensive cultivation of sugar cane, its success was such that it allowed a few years later for investments, equipping itself with an animal-drawn mill for the manufacture the type of raw sugar know as panela, which, transported by mules, was sold in the municipal markets of San Salvador, becoming the first integral sugar company of the time (Cañas-Dinarte et al., 2009). A historical milestone in terms of technology in the sector would occur in 1882, when the El Ángel Sugar Estate was a pioneer in importing a modern mill to manufacture sugar from England, thereby establishing El Ángel as the first Salvadoran sugar mill and the first to produce white industrialized sugar. In this regard, it is important to highlight the coexistence of both technologies, non-centrifuged and centrifuged industrialized sugar.

By the 1920s, some foreign and national businessmen decided to invest resources in the purchase and development of other mills, as was the case of San Andrés, El Carmen, and El Castaño; to these companies would be added in the first decades of the 20th century, other firms, such as Los Lagartos, Prusia, Santa Emilia, La Labor, La Cabaña, La Magdalena, San Francisco sugar mills, among others (Cañas-Dinarte et al., 2009). In this way, the Salvadoran sugar landscape was configured for that time, with the industrialized operations becoming the dominant technological production regime to the detriment of the artisanal panela production. Further investments were made during the second half of the 20th century other sugar mills that have been maintained to date: Central Izalco (1964), Chaparrastique sugar mill (1982), La Cabaña sugar mill (approx. 1959), JIBOA sugar mill (1976) and The Madeleine (1965). Thus,

by 2009, the centrifuged sugar agro-industrial sector in El Salvador was made up of 7,000 cane producers and 6 mills that together generated some 50,000 direct and 200,000 indirect jobs, especially in rural areas (Cañas-Dinarte et al., 2009).

With regard to non-centrifuged sugar (panela) it is important to understand the historically marginalized production in El Salvador, a part of a sector with considerable global demand. In 2020, the leader in its production was India with 7,583,000 tons followed by Colombia - 1,002,000 tons-, Pakistan -708, 000 tons-, China -530,000 tons- and Brazil -389,000 tons- (Sánchez, 2021). In the Salvadoran case, characterizing panela production, mostly by small family businesses, as differentiated from the centrifuge industrial mills that have diversified lines that are tangential to it, is a challenge due to the economic accounting of this activity according to the Central American Uniform Customs Code (CAUCA). The importance of Colombia, as revealed by the global production data, highlights the relevance of the establishment of networks with market and non-market organizations in this country, such as CIMPA - AGROSAVIA, as a priority to increase competitiveness based on differentiation, and sustainability through innovation in Salvadoran social economy initiatives like ACOPANELA.

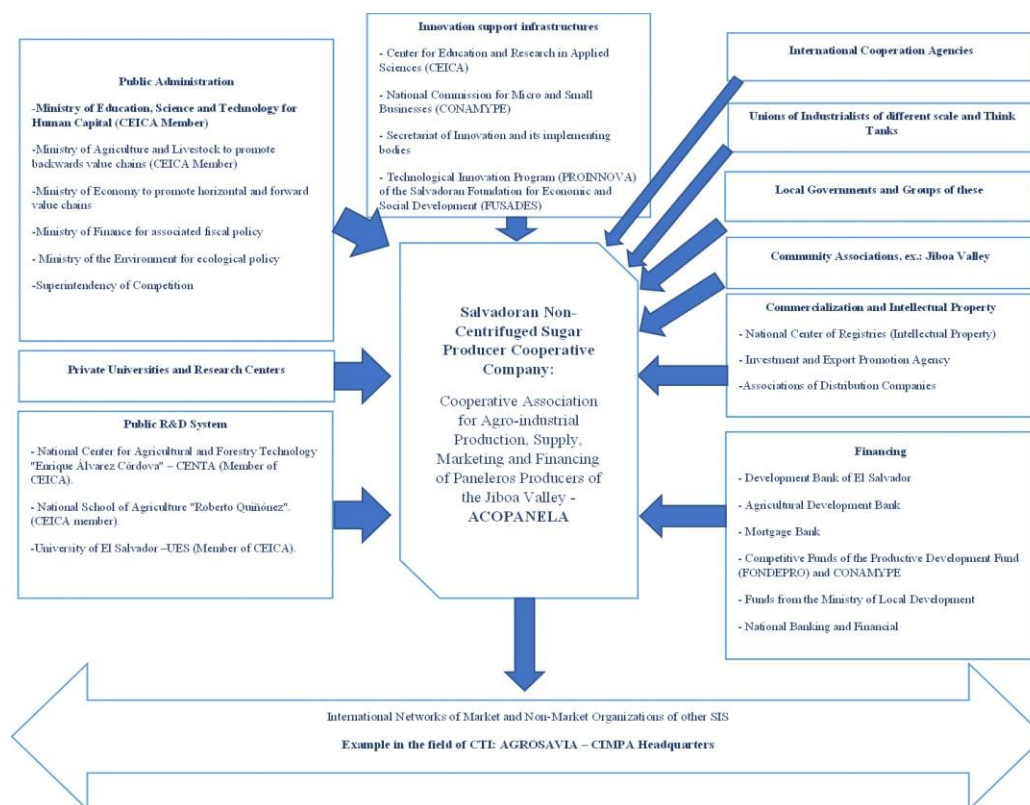
3.2. Panela in El salvador, emergence of a sectoral system of innovation and production

To verify if the panela agro-industry in El Salvador meets the requirements to be considered an emerging sectoral system of innovation and production (SIS), the status of each of its components is addressed according to Malerba's approach (2004). Regarding the main formal institutions (legislation) that affect the panela industry sector in El Salvador and its innovative processes, it is pertinent to adopt the framework proposed by the OECD (1997) that distinguishes between economic, social, and administrative institutions; as has it has been for El Salvador at another level of sectoral aggregation of food, beverages, and tobacco (Peraza Castaneda, 2019). Regarding the economic institutions, there are two major divisions, the first is related to the regulation of competition where, apart from the general regulation for the entire economy, there are two specific instruments that are relevant: 1) the Regulation of the Sugar Cane Payment System, and 2) the Regulation for the Distribution of Annual Sugar Allocations for Domestic, Preferential and World Markets. With regards to the latter, in an interview held with ACOPANELA leadership, they state that more could be done to favor their small agro-industry in terms of export quotas compared to large sugar mills. The other subdivision is related to the promotion of innovation and competitiveness, where the specific legal instrument is the Law of Production, Industrialization and Commercialization of the Sugar Agroindustry of El Salvador dating from 2001.

For its part, social regulation, integrates the environmental, safety and health, consumer protection-quality, labor and transparency aspects. With relevance for the production and commercialization of panela, the Law on Fortification of Sugar with Vitamin "A", dating from 1994, stands out as a specific legal instrument, but only for centrifuged sugar (art.2). Finally, regarding administrative regulations, they are subdivided into tax and intellectual property; where there are no specific ones for the sector, but the existing framework can be further exploited with Geographical Indications (Ruiz López & Colin Salgado, 2010).

The sectoral system's actors and their networks are revealed in Fig. 2, applying in a tropicalized way to the Salvadoran reality of panela, the sectoral innovation system approach for a developing country proposed by Essegbey & Ofori-Gyamfi (2012).

Fig. 2. Actors of the Sectoral System of Innovation of the Non-Centrifuged Sugar Agroindustry in El Salvador.



Source: adapted from Essegbey & Ofori-Gyamfi (2012)

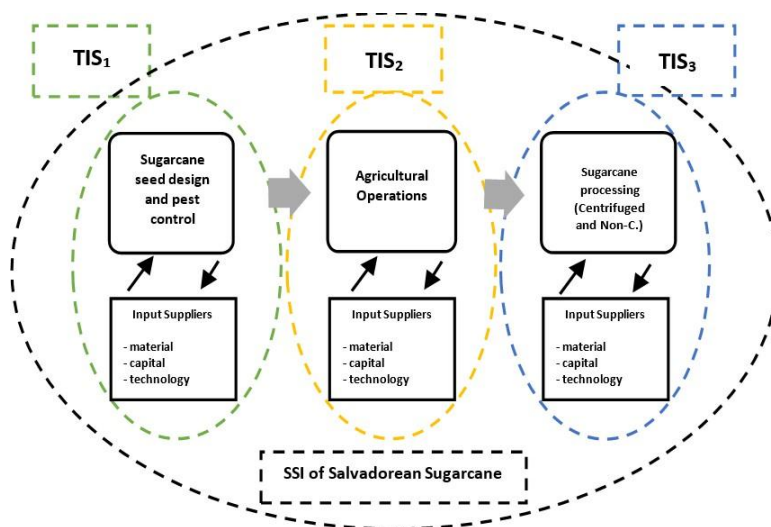
Regarding the knowledge base component, for the Salvadoran agri-food industry, of which non-centrifuged sugar (panela) is a part, the three types of knowledge are present with a preponderance of synthetic (Asheim et al., 2007). Peraza Castaneda (2019) verified this base through approximations through

science and technology indexes, concluding that their learning mode is predominately DUI.

Therefore, a latent challenge for the agri-food industry and within them the panelera in El Salvador is to incorporate more knowledge of a symbolic and analytical nature under a SIS logic, but also to consider the territorial dynamics, of what could be understood as a territorial innovation system, for example in the Jiboa Valley (Cummings, 2016). It can be argued that it is the combination of the two dynamics -DUI and STI- that generate the most positive innovative results, and that it is their simultaneous presence and combination in a complementary and synergistic way, which increases the market introduction of product innovations (Asheim, 2009). Szogs et al. (2011) argue that in the case of developing countries it is a priority to strengthen cooperation networks based on enhanced networking capacities for innovation, both nationally and internationally. As will be revealed in the more general discussion below, as well as in the ACOPANELA case where the networking capabilities prove to be a key explanatory element of the cooperative's innovative performance, its strengths as well as its limitations. Networking capabilities are shown to be integral and constitutive of the dynamic innovation capabilities of the highest order in the cooperative.

By applying Andersen's approach (2015) to the case of sugar production in El Salvador, three TISs with different degrees of development are identified (Fig. 3): 1) generation of sugarcane seed and pest control, 2) agricultural operations, and 3) sugar cane processing, where in the latter two technologies coexist: centrifuged and non-centrifuged sugar (panela).

Fig. 3. Sketch of the Sugarcane Sectoral System of Innovation in El Salvador as a union of several technological innovation systems.



Source: adapted from Andersen (2015).

As will be seen below in the more analytical section of the case study, the main challenge for the panela agro-industry in El Salvador is to strengthen TIS 1 and 2. While the one with the greatest technological catching up is TIS 3, promoted by the link with CIMPA- AGROSAVIA.

3.3. ACOPANELA – Networking capabilities to innovate as a source of sustainable competitive advantage.

ACOPANELA began its operations in 2004 with 17 producers as cooperative members. Its initial purpose was to market the solid panela product at a better price in stable dynamic markets to guarantee improved income and thus a better quality of life for producers and consequently avoid the disappearance of panela as a traditional local product (Interview with president of ACOPANELA in February 2022). This implied the development of a product with Salvadoran “ethnic” characteristics that could also meet better manufacturing, export quality standards.

The challenge was that, although the ACOPANELA collective was motivated to innovate, they had limited knowledge of the market and the technological opportunities that were emerging in parallel in other parts of the world, including Colombia, as a center of excellence for Latin America (Cummings & Cogo, 2012). From the perspective of evolutionary economics, there was an effort to organize the family artisan production units – *trapiches or moliendas* - into a social economy cooperative enterprise, in order to rescue and revive the culturally rooted base for their family livelihoods and as providers of scarce local employment. Through the strengthening of their capabilities for resilience and proactive response to the crisis of unstable markets and the earthquakes in 2001 that destroyed the productive capabilities of many *trapiches*, ACOPANELA was able to save their small agro- industry in the face of "creative destruction" (Schumpeter, 1943) that began in 1976 with the start-up of the centrifugal industrial sugar processing industrial plant - Sugar mill Jiboa in the Jiboa Valley region.

The emergence and evolution of ACOPANELA implied innovation in the institutions, routines, common habits, established practices that regulated the relationships among actors of family businesses, under the logic, rules, laws and norms that applied to them as members of the cooperative, making decisions about how to participate in different its governance and whether to make the investments to upgrade their own panela production operations to meet the requirements to be suppliers of the productive and commercial operations of the cooperative. These new institutional rules of the game were relevant guiding their behavior as actors participating in innovative processes (Edquist, 1997; Nelson & Sampat, 2001).

Once the small agro-industrialists were organized in ACOPANELA, they introduced better manufacturing practices and built the first "model mill", with

the capacity to meet the demands of dynamic, national, and international markets, offering a traditional, "ethnic", hygienic, uniform, high-quality product. In this process the first expressions of the innovation capabilities that ACOPANELA was building emerged and were strengthened as a crucial step in the long process that began with the discovery of granulated panela as an innovative alternative, with important advantages and complementarities with the commercialization of traditional solid presentation "*dulce de atado*", including a dynamic demand in the international market for natural sugars. Along this path, the ACOPANELA cooperative had to face several challenges including the fact that the necessary investments to modernize the traditional mills to produce the required quality and quantity of solid and granulated panela for export were not feasible for many cooperative families. Thus, the potential innovative process seemed to have reached a dead end (Cummings & Cogo, 2012).

The solution to this challenge in the implementation of ACOPANELA's innovative process would come through the strengthening of its networking and interactive learning capabilities. As Van Geenhuizen & Nijkamp (1999) argue, the practice of networking is reflected in the intentional participation of ACOPANELA in networks, the formation of new networks and the dissolution of old ones in order to achieve their objectives; for example, the production of solid panela with good manufacturing practices for export and granulated panela in a new processing plant with Colombian technology.

Arocena & Sutz (2000) argue that in the "neo-periphery" of the global system, where El Salvador is located, the elements of an innovation "system" are fragmented and weak, and thus the system as such, exists in an emergent state. The scope of the capacities of the national and sectoral systems of innovation for agriculture, including small rural agro-industry, is weak (see Cummings, 2007); and thus, the need for actors that mediate innovative knowledge between economic initiatives of peripheral territories and national or international centers of excellence, as is argued by Szogs, Cummings and Chaminade (2011). For small-scale agro-industrial initiatives such as ACOPANELA, evolutionary economics indicates that their effectiveness in innovating and thus obtaining a competitive advantage will depend to a large extent on their accumulation of networking capabilities to materialize potential synergies both among members of the cooperative, as well as from it to its external partners (Porter, 1990).

The case of ACOPANELA is especially interesting in that it is the cooperative as such that acts as an intermediary organization for innovative knowledge, to gain access and integration of complementary aspects in the knowledge, skills, and specialization of CIMPA - AGROSAVIA as Colombia's center of excellence for the global panela value chain, as Edquist (1997), Lundvall (1992) and Teubal et al., (1991) argue for innovation networks. In this sense, a key milestone for

ACOPANELA was learning about innovative technological trajectories (Dosi, 1988) to produce granulated panela in Colombia, and from this point of departure, putting into practice its networking capability with panela producers and technical experts from that country. Thus, after its initial reconnaissance trip to the CIMPA center in a key panela producing region of Colombia, ACOPANELA was able to mobilize resources for a second visit designed specifically to learn about the process of making granulated panela directly with CIMPA's technicians, and in a dialogued interactive learning process with Colombian panela producers implementing their technologies.

During this second visit, the ACOPANELA leadership negotiated the participation of technicians related to CIMPA in the first project financed by the Multilateral Investment Fund of the Inter-American Development Bank (IDB - FOMIN), "Production and Marketing of Granulated Panela from the Jiboa Valley". The technical assistance financed by this first IDB project enabled ACOPANELA to improve traditional trapiche production and develop alternative products, where once again its relationship and linkage skills, now with a financier, were key. The president of ACOPANELA highlights that "they were not looking for someone to bring, we already had the contacts" which is why they were able to employ as project consultants "technicians suited to our needs" (Interview with the president of ACOPANELA in February 2022). ACOPANELA's relationship with actors from the CIMPA-AGROSAVIA continued in a second technical assistance project financed by the IDB aimed at building and establishing productive operations in a plant for granulated panela: "Industrialization, Technological Development and Commercialization of the Panela Sector". After validating the processing technology to be implemented, the necessary financing for its implementation was mobilized through ACOPANELA's networking capabilities; this time with the Salvadoran Ministry of Economy and a national bank (Banco Hipotecario), to make the necessary investments to implement the innovative knowledge provided through the second IDB-FOMIN project.

ACOPANELA was thus able to avoid a dead end, to their innovative pathway of upgrading each family mill with investments required, but not feasible to carry out in many cases to achieve export certification for its products; and to create a new technological trajectory by establishing a medium-sized semi-industrial plant that produces export-quality granulated *panela*. The current president of ACOPANELA states that initially they bought pre-cooked molasses from evaporated sugar cane in the *moliendas* of members that qualified as suppliers (Interview with the president of ACOPANELA in February 2022). However, through experimentation and learning by doing, they made the decision to buy cane from them, of the variety and with the agronomic process indicated for granulated panela and process it to generate precooked molasses in the two mills initially known as "model" with greater investments in productive capacity and for the implementation of good

manufacturing practices, before finalizing the production of granulated panela in the Colombian technology plant. Thus, the development of granulated panela as an innovative product in ACOPANELA was a cooperative effort that none of the individual sugar mill owners could have achieved individually. Collectively, they also would not have been able to do this without their connections through external innovation networks. To produce the "*dulce de atado*" that are packaged and marketed as "ethnic" products in the market of Salvadoran migrants in the US, they always occupy the mills of their paneleros members who comply with basic hygiene requirements to guarantee the quality required for export.

The innovative dynamics of ACOPANELA provide greater economic sustainability to family production in the small mills that qualify as suppliers, allowing families to maintain the cultural value of their production processes for their community identity, as well as to project their potential as a basis for generating rural community tourism along the "*Ruta de la Panela*" (Cummings & Cogo, 2012). These dynamics have also stabilized the market price for the broader set of panela producers and thus positively impacted the multidimensional well-being of these families, members or non-members of ACOPANELA (Interview with the president of ACOPANELA in February 2022).

The case study of the social economy initiative ACOPANELA demonstrates how in the Global South it was possible to establish a sustainable competitive advantage by achieving progressive innovative improvements in the production and commercialization systems of *panela*, sustaining it through a synergistic relationship between learning capacities and networking of this cooperative in order to:

- i. Develop and take advantage of the endogenous knowledge base to identify and access innovative knowledge from an international center of excellence and other sources of the existing sectoral innovation system in its fragmented form for panela in Latin America.
- ii. Identify and capture alternative innovative technologies as solutions to performance problems that threatened the creative destruction of the livelihoods and socio-cultural identity of panela producing families in the Jiboa Valley.
- iii. Locate and mobilize the necessary financial resources to implement these innovative technological changes, highlighting the value of their networking connections with national and international financial actors.
- iv. Start a process to dynamically assimilate these exogenous elements in innovative initiatives, but without losing and instead reinforcing the

value of their synthetic and symbolic knowledge of territorial roots as *panelera* business families.

The current challenges for ACOPANELA and the small-scale panela agro-industry in general include continuing to strengthen their networking and interactive learning capabilities to deepen the dynamic assimilation of evolving innovative knowledge into their technological innovation systems (TISs) related to processing, but also generation of sugarcane varieties and other agricultural operations in the global panela value chain, as argued by Andersen (2015) (see technological innovation systems 1, 2, and 3, of Fig. 3). It is thus considered that the dynamics of ACOPANELA in El Salvador are a contribution of this initiative of the social and solidarity economy to the holistic sophistication of the sectoral system of innovation for the production and commercialization of panela, both solid and granulated, in Central America and Latin America more broadly.

The COVID19 global pandemic crisis represented significant challenges for ACOPANELA. During the 2020-2021 production cycle, it focused on guaranteeing production, while for 2021-2022 the challenges had more to do with marketing since the closures of the economy during the first cycle meant that many of their customers still had inventory. In order to face these challenges, as always, they are making use of their networking and interactive learning capabilities, and plan to acquire another technologically innovative sugar mill from Colombia, improve packaging, and gradually begin a digital transformation in its marketing scheme with the creation of a web page (interview with the president of ACOPANELA in February 2022).

4. Conclusions

The panela sector has historical roots in El Salvador, demonstrating in the Jiboa Valley a significant resilience in the face of the forces of creative destruction brought on by the dominance of centrifuged sugar in the 20th century. Some initiatives such as the ACOPANELA cooperative have been able to adapt and dynamically assimilate advanced innovative knowledge as the basis to face and overcome multiple challenges along the way. The evidence discussed supports, on the one hand, the existence of a sectoral system of innovation and production of panela (solid and granulated) although it is still in an emerging, fragmented state and with weak territorial roots. On the other hand, it shows that, in order for this small rural Salvadoran agribusiness to successfully face its current and future challenges, ACOPANELA's capabilities to work and learn in networks could be considered the most important resource and the construction of these networks (especially with centers of excellence in global value chains), as the most important process in its innovative dynamics (Szogs et al., 2011, Cummings, 2007).

Acknowledgment

We appreciate the interest and collaboration of the ACOPANELA leadership team who took time in their schedule to talk and share their valuable knowledge about the evolution of the cooperative and the quality of its relationship with CIMPA - AGROSAVIA: Antonio Hernández, founder and president, Merlin Cerros, manager and Mauricio Meléndez, ex manager and advisor. We also acknowledge the contribution of Eleonora Cogo as a researcher and co-author of the academic text that analytically characterizes the nature, dynamics, and innovation capabilities of ACOPANELA.

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Note

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- ¹ Colombian Corporation for Agricultural Research, which is a Science, Technology and Innovation entity that contributes to technical change to improve the productivity and competitiveness of national agriculture.

The rise and fall of innovation systems in Africa: Case study from the tanga dairy innovation system in Tanzania

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1. Introduction

African countries, including Tanzania, lag far behind in terms of technological advancement (Muchie et al., 2003). For instance, in many African countries, traditional technology and knowledge are still used in productive sectors. This has resulted in a failure to adequately produce the quality and quantity of products required by local and international markets (Wangwe, Diyamett, & Komba, 2009). This situation has arisen as a result of the presence of systems with weak and underdeveloped linkages, which pose a significant threat to competitiveness and growth (Lundvall and Borrás, 1999). According to research, existing productive sectors and firms, for example, have low levels of interaction with universities and technology service providers (Coulson & Diyamett, 2012). Similarly, informalities in business and the dominance of micro and small enterprises are key distinguishing features of Africa's innovation systems (World Bank, 2017). In general, systems of innovation in most African countries are still in the infancy stage (Lundvall et al., 2009). The majority of organizations (both formal and informal) are emerging that require critical setups to facilitate their linkages and interactions.

This paper focuses on Tanzania's Dairy Innovation System to substantiate the above claims. Despite having a large cattle population, Tanzania still imports a large amount of dairy products. To back up the claim, NIRAS (2010) found that imports have been increasing by about 9% per year, while the amount of locally

processed milk has decreased by more than 80% over the last 15 years. As a result, Tanzania spent more than USD 40 million in 2014 on milk and milk products imports (ANSAF, 2016). This has been largely attributed to a lack of innovation capacity, a low rate of technology transfer, and potential technical inefficiency in current dairy production practices caused by weak links between milk producers and processors (Nyaki, 2014).

Since 1980, efforts have been made to improve linkages in order to boost the technological capabilities of small-scale dairy farmers and milk processors throughout Tanzania. Donors and development agencies were invited to Tanzania to help the industry through a variety of projects. The Dutch government agreed to support the Kagera Smallholder Dairy Development Project and the Tanga Smallholder Dairy Development Project at this time. The Swiss government supported the Southern Highlands Dairy Development Project, and the German government supported the Lushoto Smallholder Dairy Development Project (Kago, 2015). With the exception of the Tanga Dairy Development Project, most of those projects had a limited record of success. In other words, only the Tanga dairy production system stands out as an example of an innovation system with success stories that evolved over decades and demonstrated positive outcomes in terms of farmer-processor linkages in these projects (Nell et al, 2014).

The Tanga dairy Innovation system evolved into a strong production system in which farmers are able to supply the required quality and quantity of milk for processing (forward linkages) to Tanga Fresh in exchange for technical support and credit flows from Tanga Fresh LTD (backward linkages). Several studies have investigated the success factors of the Tanga dairy agro- industrial innovation system using the innovation system framework (Nell et al., 2014; Akyoo et al., 2016 Baregu, 2017). Many of those studies, however, suggest that the system's success is attributed to the diffusion of improved technologies and techniques to dairy farmers, such as the adoption of zero-grazing, cross-breeding, access to inputs such as minerals, and improved feeding practices, and disease control practices. However, the literature appears to have ignored the discussion and analysis of the role of enabling environment in stimulating and maintaining strong institutional cooperation and linkages among the actors which is critical to the diffusion of improved technologies and innovations.

Likewise, starting in 2016, the system started to perform poorly. The output began to fall, and some actors made the decision to leave the system. There has no scholarly research done to explain why the system is failing. To close these two information gaps, this study was designed to investigate the variables behind its rise and decline. Two primary research questions were addressed by the study: How did the Tanga dairy innovation system develop, and then why did it fail? The paper is organized as follows: The first section is an

introduction, Section 2 is a literature review, and Section 3 discusses the research methodology. Section 4 presents data. Section 5 discusses the findings. The final section discusses the Tanga Dairy Innovation System in Tanzania.

2. Literature review and theoretical framework

2.1 Efforts to develop the dairy sector in tanzania: Trends and challenges

Historically, efforts to develop Tanzania's dairy sector began during the colonial era (Njombe, 2010). The British government in Tanganyika allowed settler dairy farmers to establish Temeke dairy farm in Dar es Salaam in 1921 (Macharia 2015) to supply milk to the government's civil servants in Dar es Salaam (Kurwijila, 2001). From 1920 to 1940, the "white highland" dairy project was established, covering the highlands of Arusha and Iringa. From 1932 to 1935, the Mpwapa Livestock Research Station developed the Mpwapa breed based on Indian, European, and Tanzanian breeds for semi-arid regions with a higher potential for milk production. Unfortunately, almost all of the animal breeds were kept within the research stations, and there were no serious efforts to disseminate them to local farmers (Kurwijila, 2001).

Following independence, the dairy sector received greater government attention, and the Dairy Industry Ordinance (No. 61 Cap. 456 of Tanganyika's laws) was drafted in 1961 to regulate the dairy industry. The law proposed the formation of Zonal Dairy Boards to regulate milk production and processing in areas that produced enough milk (Sumberg, 1997). Furthermore, the government recognized a growing gap between domestic milk production and national milk demand in 1965. This resulted in the Tanzanian Dairy Industry Act No.32 of 1965, Cap.590 of which recommended the establishment of a government-controlled National Dairy Board (NDB) and emphasized the establishment of large-scale and medium dairy farms. By 1973, it was clear that the NDB had failed to improve the country's milk production and processing. As a result, its operations ceased that year (Kago, 2015).

Part of the structural changes that occurred during the 1980s included the transfer of production, marketing and processing, and other business-related functions from state institutions to private sector actors. Other partners, such as donors and development agencies, were invited to assist the industry through various projects. During this time, the Dutch government agreed to support the Kagera Smallholder Dairy Development Project and the Tanga Smallholder Dairy Development Project. The Swiss government supported the Dairy Development Project in the Southern Highlands, and the German government supported the Smallholder Dairy Development Project in Lushoto (Kago, 2015). With the exception of the Tanga Dairy Development Project, the majority of those projects had a mixed record of success. According to Neil et al. (2014), most dairy farmers in Kilimanjaro, Kagera, Iringa, and Morogoro continue to

rely on traditional dairy farming practices due to a lack of access to inputs, extension service providers, marketers, credit providers, and training centers.

According to Njombe et al. (2011), the dairy subsector in Tanzania has failed to take off despite efforts, owing to a lack of clear strategies for stimulating business model development and maintaining strong linkages among the actors in the dairy value chain. Given the lack of proper coordination, various actors in the sector maintained their traditional roles. Furthermore, a study conducted by Baregu (2017) revealed that the sector's challenge of low capabilities was attributed to poor coordination of the sector's actors. This implies that a clear strategy for coordinating the actors is critical for the development of Tanzania's dairy industry.

2.2 Addressing the challenges in dairy industry: An innovation system perspective

The innovation systems theory/approach is the most effective tool for analyzing the actors, networks/linkages, and institutions that influence innovation processes in an industrial sector. Because of its utility, the theory has been applied in other sectors of the economy, including agriculture (both crops and livestock) as a framework for enhancing innovation in both raw input production and subsequent processing. This approach emphasizes the interaction of diverse actors during the generation, exchange, and use of agricultural-related knowledge for economic relevance (World Bank, 2006). According to Leeuwis (2004), the system influences innovation through an interactive learning process among multiple actors who are networked and linked with the help of a supportive environment. Hidalgo and Albers (2008) contend that networks and linkages to generate social learning either through “using”, and “doing” or sharing and knowledge exchange among the actors in the system.

Innovation is defined as the process of creating, accessing, and applying knowledge and information to create new products, processes, services, and so on that meet social and economic goals (Hall et al., 2009). The question now is not only about developing new knowledge, but also about the ability to mobilize and apply existing knowledge. This shifts the emphasis on technology and agricultural production techniques to networks, linkages, and institutional environments that enable the integration of different knowledge sources and the adaptation of introduced technologies to meet the requirements of the specific sector.

According to Jensen et al. (2007), innovation can be divided into two types of learning. The modes of learning are STI (Science, Technology, and Innovation) and DUI (Doing, Using, and Interacting). The STI model focuses on codified knowledge, formal learning processes, and experimentation-based learning.

Formal training, interaction with science and research organizations (such as universities), and R&D are almost always the sources of STI modes of learning. DUI modes of learning, on the other hand, refer to workplace learning and the transfer of tacit knowledge as a result of interaction with users. Establishing social capital in relationships and developing networking capabilities to facilitate interactive learning among the various actors is critical in both cases. However, in African contexts, the nature and gaps between the respective knowledge bases of the various actors involved may necessitate the use of an enabler, such as a contractual arrangement, to facilitate the development of networking capabilities.

Both forms of interactive learning occur in well-functioning innovation systems under a variety of agreements between producers and processors, leading to the acquisition of new knowledge and competencies that can be applied to innovative practice. According to Zsogs (2008), the basic interactions in an innovation system are those that occur between (a) producers and buyers; (b) multinationals (MNEs) and indigenous firms, typically small and medium-sized enterprises (SMEs); (c) among SMEs; and (d) between SMEs, universities, and other public and private business and technical knowledge providers. This paper focuses on the interaction model between producers and processors. The model assumes that the interacting producers and processors/buyers have the in-house capabilities to absorb and benefit from the knowledge and information shared during the collaboration (Fagerberg, 2004). However, in Africa, producers and processors/buyers only interact when selling and buying products. Here is where the issues with the quality of the products and the quantity required by the buyer begin. They lack knowledge transfer from the manufacturing cycle to the selling and purchasing stages.

2.3 Approaches used in stimulating actors' linkages in the AIS: Empirical evidences

Actors are individuals or organizations, in the public or the private domain, that have the ability to cause change. In the AIS, the following may be the actors; smallholder farmers, inputs and services providers, processing enterprises, organizations that influence policy (Bureaus of agriculture, education, finance, industry and trade), buyers, R&D, Universities, extension and training services and farmers associations. Several approaches have been applied to link the actors in AIS as described below.

First, the use brokering or intermediary agent—these acts as a 'lead operator' — who organizes and manages networks; and also, as a 'caretaker' — who maintains the integrity of the network domains (research, enterprise, users and infrastructure) (Klerkx and Leeuwis, 2008). Intermediaries have been viewed by Winch and Courtney (2007) as "a member of the network of actors focused not only on the generation nor the implementation of innovations, but also on

enabling other actors to innovate". They take a facilitator role in arranging the actors to allow the knowledge flow from one entity to another. The case studies of cassava and cut flowers innovation systems subsectors in Colombia by Rajalahti et al (2008) were found to function well, evolving from traditional subsistence crop systems into agro-industrial systems. The success stories of these innovation systems are the result of cooperative intermediaries (apex associations) that have linked and organized small-scale farmers, processing firms, market, national and international research organizations, the government, and financial organizations into production systems.

Second, the use of contractual arrangements – This is an agreement of actors (whether formal or informal) on how to operate in certain production system. It is argued by FAO (2013) that many contractual arrangements create linkages that allow information, material, technical support, credit flows, market access and skills among the system actors. A study by Mintenet al. (2009) on French beans innovation system in Madagascar discovered that the important role of contractual arrangements towards the system's performance. The Lecofruit Company had signed a contractual arrangement with the farmers on the purchase of French beans to be exported to the European supermarkets based on international standards specified. In meeting food safety and agricultural health standards imposed by Europeans supermarkets, Lecofruit trained farmers on how to produce quality products by locating extension officers to every 30 farmers. On average, each smallholder farmer was to be visited more than once per week by one of the firm's representatives, who would sometimes carry out specific activities themselves, for example, applying pesticides on the crops, so as to ensure that it is rightly done. The contractual arrangements are perceived to have triggered linkage capabilities of the system actors that improved the technological capabilities of the French beans farmers (Mintenet al., 2009).

Public-private partnership - The model stimulates the linkages between public and private actors in order to transfer knowledge, technologies, information and related resources across actors in the innovation system or the product value chain. Zahran et al (2020) unveiled linkages through public-private partnerships as the leading approach used to strengthen Agricultural Knowledge and Innovation System (AKIS) in Dakhalia governorate of Egypt.

The literature explains how various models helped the evolution of systems of innovation in developing nations, such as Tanzania's Tanga-dairy industrial system, which turned those systems into a well-organized and competitive system while maintaining strong institutional cooperation and links among key system actors. However, there hasn't been much scholarly research done to explain why the same systems of innovation have been failing. This study aimed to fill this knowledge gap.

3. Research methods

This exploratory research study used a variety of methodological approaches to evaluate the innovation system perspective in light of existing knowledge about the Tanzanian dairy sector, specifically the Tanga dairy system. In response to the study's first research question, relevant data and information were gathered from several actors involved in the Tanga dairy innovation system, with a focus on their specific roles and behaviors. The background analysis focused on system formation from historical to current processes, characteristics of the main actors, and information, knowledge, and resource linkages and flows. Furthermore, the arrangements and interactions between formal and informal actors in this dairy innovation system were investigated.

Moreover, the survey assessed farmers' access to information on market dynamics, extension services, veterinary medicine, other veterinary services, and milk collection, storage, and transportation technologies. The study investigated the dairy processors' firm-level capability to improve its product range, shelf longevity of its dairy products, marketing innovation, improvement of milk processing methods, improvement of processing technologies, access to new markets for processed dairy products and challenges encountered the system. The survey focused on the existing agreement between dairy producers and processors, farmers' ability to adopt and implement improved feeding practices, improved breeding practices, and improved dairy management processes.

Concerning the second question why did it fail, the study concentrated on challenges facing the system now. A survey of 100 dairy farmers from Muheza district who supply Tanga Fresh LTD was conducted. From 2020 to 2021, all of these data were gathered through questionnaires, interviews, site visits, and Focus Group Discussions.

The Nvivo software package was used to organize the qualitative data into themes, patterns of innovation diffusion, and technological capacity building among farmers. The data was then exported to MS Excel Software for presentation purposes, where graphs and charts were created. The descriptive statistics from the dairy farmer survey were used in the quantitative analysis of the survey data. This includes categorization, a central tendency measure, tabulation, and cross-tabulation.

4. Research findings

4.1. Evolution of tanga dairy agro-industrial innovation system (the rising phase)

Tanga Dairy Agro-Industrial Innovation System had evolved into a well-organized and competitive system that has thrived for more than three

decades. From 1985 to the present, the system evolved and went through four major phases of development. Because of its distinct development trajectory, this section explains the system's evolution from 1985 to the time the study was conducted (2021), as well as the characteristics that distinguish each stage. While acknowledging the existing literature on the Tanga dairy system, it is important to note that the analysis and some empirical data presented in this section have not been previously documented.

4.2.1. Development of the system phase 1. dairy farming capability building to small farmers (1985-1992)

Tanga Region, like the rest of Tanzania's coastal regions, is not a traditional pastoralist community. It wasn't until the late 1970s and early 1980s that some commercial dairy farms, such as Azimio, Mgwisha, Kange Buhuri, and Tanga Dairy, were established with Dutch government assistance (Interview with TDCU leaders, 2019). Nonetheless, by the mid and late 1980s, support had shifted to small-scale dairy farmers, who were more efficient than parastatal large-scale farms. The Tanga Small Holder Dairy Development Programme (TSDDP) was established in 1985 with financial and technical support from the Tanzanian government and society from the Netherlands. At BUHURI livestock institute, small-scale farmers were organized and trained on recommended dairy farming practices as part of this program.

TSDDP introduced Artificial Insemination to small-scale farmers as a breeding service for livestock improvement (Interview with former BUHURI extension officer, 2019). Furthermore, with financial assistance from the Netherlands, the program established the cattle credit system in 1985 to encourage farmers to engage in dairy farming for increased milk productivity. Some of the dairy farmers interviewed for this study confirmed receiving such credits as their initial investment in the industry (Interview with Farmers, 2019).

The training and cattle credit system aided farmers in developing intermediate technological capabilities. It gave them the ability to produce milk for domestic consumption as well as sell it locally to Tanga's surrounding communities, as well as neighboring schools and hotels. Similarly, some refrigerated raw milk was transported as fresh milk to Dar es Salaam. TSDDP encouraged farmers to form primary cooperatives as an improvement to the traditional system.

4.2.2 Development of the system phase 2. establishment of tanga dairy cooperative union (1993- 1996)

In 1993, six dairy farmers' primary cooperative societies established in phase one merged to form Tanga Dairies Cooperative Union, an apex organization (TDCU). This organization was tasked with achieving the following goals: developing dairy farmers' milk production skills and capabilities, protecting the benefits of primary cooperatives, ensuring a stable market for milk

produced by TDCU members, selling milk produced by members, facilitating dairy input availability at a reasonable cost to farmers, and milk price negotiations for the benefit of its members. During this phase, actors such as Farm Friends Tanzania, TALIRI, and Buhuri Livestock Agency began to collaborate with TDCU by offering and supporting training, credit, research, and technology transfer to its member small-scale dairy farmers. TDCU oversaw the cattle credit system by implementing a new type of operational innovation. Under the new scheme, each registered farmer received one cow or heifer as a loan, with the obligation to care for such animals until parturition. In this case, payments for such cattle credit were made by deducting 70% of the income generated by milk sales to TDC each month until the loan was paid off. Similarly, TDCU became the primary buyer of milk from farmers, and the milk was collected through their primary cooperatives, which established and operated the Milk Collection Centers (MCC). TDC sold the milk collected in Dar es Salaam as fresh milk and a traditionally cultured yogurt. This arrangement lasted until 1997, when Tanga Fresh Limited was formed. During this phase, the cooperative's membership grew, and five (5) new primary cooperatives were established. Unfortunately, no record of the amount of milk produced and collected by TDCU during this time period could be found.

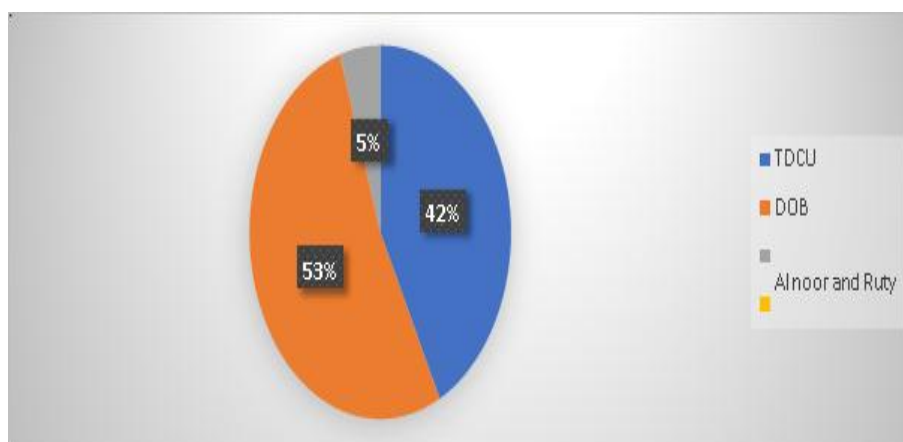
4.2.3 Development of the system phase 3. processing capability-establishment of tanga dairy processing plant, branding and consolidation (1997 -2007)

Dairy Cooperative Union (TDCU) collaborated with the Friesian cooperative society from the Netherlands in 1996 to establish a milk processing plant, which was registered as Tanga Fresh LTD. Tanga Dairy was founded with significant support from the Dutch society and several non- governmental organizations in the dairy sector. Farmers gained the ability to produce the required quantity and quality of milk for processing during this phase. Tanga Fresh Limited, which processed and produced dairy products such as fresh milk, cultured milk, butter, cream milk, plain yogurt, and flavored yogurt, became the main buyer for TDCU milk beginning in 1997. The plant was designed to process 15,000 liters of milk per day. The processed products were primarily sold in Dar es Salaam. In terms of ownership, TDCU held 35%, Friesian cooperatives held 55%, and Tanga Fresh LTD Directors Alnoor and Rutu held 10% (TDCU, 2019). With the help of industrial innovation and a larger market, the amount of milk collected by TDCU gradually increased from 2 million liters in 1999 to 7.5 million liters in 2007. This was caused by an increase in the number of dairy farmers, which resulted in the establishment of new local cooperatives and Milk Collection Centers (MCC).

4.2.4. Development of the System Phase 4: Improvement of Innovation Capability of the System (2007 to present)

The Dutch Oak Tree Foundation (DOB) from the Netherlands purchased Frisania Invest Cooperate's shares in 2007 and formed a joint venture with TDCU in milk processing at Tanga Fresh Company. Based on the newly injected capital, TDCU's share in Tanga Fresh Ltd increased to 42.5%, DOB acquired 52.5%, and management (Directors), Alnoor, and Ruty's shares decreased to 5% from 10%.

Figure 1: Shares of the tanga fresh ltd.



Source, Field data, 2021

The new investor (DOB) purchased a significant portion of the milk plant and invested three million euros in refurbishing the factory, purchasing and installing new equipment and cooling facilities in MCC such as cooling tanks, standby generators, trained personnel, and refrigerated milk transporting trucks. The funds were also used to purchase additional transport vehicles for collecting milk and transporting it to Dar es Salaam for sale and distribution.

During this phase, milk collected increased from 7.5 million to 14 million liters per year on average. Milk collection has increased due to increased membership, including the formation of new primary cooperatives and MCC. With approximately 4,500 farmers concentrated in one area, TDCU currently had 26 primary cooperatives, making the Tanga region a major dairy shed in Tanzania (TDCU, 2020).

Tanga Fresh increased its daily processing capacity from 15,000 to 31,000 liters in 2010. Between 2012 and the time the study was carried out in 2019, milk processing capacity increased to 50,000 liters per day. The increased processing capacity is due to the installation of a processing machine with a daily capacity of 150,000 liters, as well as an increase in dairy farmers' ability to produce enough milk to feed the processing plant. Tanga Fresh Ltd produces pasteurized fresh milk in half-liter and one-liter packs, cultured milk, butter,

cream milk, plain yogurt, and flavored yogurt. Tanga Fresh sells only 25% of its products in other regions such as Arusha, Kilimanjaro Dodoma, and Zanzibar. The study confirmed that Dar es Salaam dominated the market for Tanga milk and other dairy products at all four stages of system development (Tanga Fresh Ltd, 2020).

4.3 Formation of backward and forward linkages in tanga dairy-agro industrial innovation system

The study found that the Tanga-dairy industrial system had evolved into a well-organized and competitive system while maintaining strong institutional cooperation and linkages among key system actors. Small dairy farmers, Buhuri training centers, extension service providers, TDCU, Tanga Fresh Limited, TALIRI research institute, Agricare Enterprise and Marenga (input providers), credit providers (FARM Friends Tanzania, FINCA Bank), NGOs (MEDA), and development partners (SNV) were among those actors. As a result, the study looked into how these actors' links were formed and managed in the system. It was found that the linkages are/were formed, coordinated, and managed by key system actors through contractual arrangements (both formal and informal). TDCU was the "leading operator" in network organization and management, as well as a "caretaker" in ensuring the integrity of the network of actors and their roles in the system.

It was discovered that TDCU and Tanga Fresh Ltd had formal contractual arrangements under which Tanga Fresh settles the dairy farmers' bills through TDCU. At the same time, TDCU collects raw milk from smallholder dairy producers via MMC, and Tanga Fresh transports it to the factory to be processed into various products. In terms of payment, the agreement was that after transporting milk to Tanga Fresh Limited and collecting data on quantities collected, Tanga Fresh Limited would pay TDCU, and TDCU would send payment information to each primary cooperative leader. Then, through cooperative leaders, each farm receives its payments. Furthermore, as part of these agreements, TDCU and Tanga Fresh agreed to work together to provide dairy farmers with training and inputs (Tanga Fresh does not deal with farmers directly). According to the study, the MCC has a contract with the milk cooperatives under TDCU, and approximately 80-90% of the milk they collect goes through this channel. Tanga Fresh Ltd, on the other hand, has installed new equipment and cooling facilities in these MCCs, including cooling tanks, backup generators, trained personnel, and refrigerated milk transporting trucks. The arrangement is consistent with the factory's ownership, with TDCU holding 42.5% and DOB holding 52.5%.

Similarly, TDCU has a formal contractual arrangement with dairy farmers under which TDCU collects milk from small dairy farmers on behalf of Tanga Fresh Ltd, provides inputs, trains farmers on animal husbandry, lobbys and

advocates for the interests of its members, and provides extension services. To access these services, dairy farmers must first register for TDCU membership, which comes with a mandatory entry fee of 10,000 Tsh. The funds are either paid directly or deducted from the milk supplied to the cooperative.

Furthermore, the study found that TDCU signed a contract with AGRICARE Enterprise to supply farmers with inputs such as animal feeds and veterinary drugs. Other institutions, including FARM FRIENDS TANZANIA and FINCA BANK, entered into various contractual arrangements with TDCU to provide farmers with cattle credit and other soft financial loan facilities. In these cases, repayment is accomplished by deducting a portion of milk sales. Furthermore, TDCU is working informally with some NGOs, extension officers, Buhuri Training Institute, and TALIRI Research Institute Training to provide capacity-building services to member dairy farmers, such as seminars on livestock husbandry, cattle disease surveillance, and management.

4.3.1 Linkages roles to dairy farmer's technological capability building

On the initiatives taken to improve the capability of dairy farmers in milk production findings from the fieldwork indicated that this was achieved through linkages established under the contractual arrangements (both formal and informal) aimed at facilitating technology transfer, training of skills, and improving access to input among the dairy farmers from the various actors in the system.

Table 1: Activities taken to improve farmer's technological capabilities

Activities to improve Capabilities	Responses	
	N=	Percent
Training	86	34.0%
Extension services	62	24.5%
Demonstration model farm	24	9.5%
Seminars	78	30.8%
Exhibitions	3	1.2%
Total	253	100.0%

Source: Field Survey, 2021.

The multiple responses from respondents summarized in Table 1 indicated that 34% of dairy farmers received training, 24% were contacted by extension officers, 9.5% had an opportunity to visit a demonstration model farm, 30.8% had attended seminars and 1.2 % had attended exhibitions. In most cases, a

training course is delivered in 2 weeks classroom program at Buhari Training Centre and embedded with a delivered farming demonstration manual. Interviewed farmers reported that illustrative training manuals were more useful, and they enabled most of them to follow the instructions given.

Table 2: Actos collaborated in building the farming capability of dairy farmers

Actors Implemented the activities	Responses	
	N	Percent
TDCU in collaboration with Tanga fresh	45	36%
TDCU in collaboration with other actors i.e., research institutes, NGOs, and input providers	81	64%
Total	126	100%

Source: Field survey, 2021

Farmers' capacity-building activities were stimulated by the existence of strong linkages among the actors who collaborated in implementing the activities. Table 2 indicates that 36% of the respondents had received training through TDCU in collaboration with Tanga Fresh Ltd. On the hand, 64% of the respondents indicated that they had undergone training through TDCU in collaboration with other actors such as TALIRI, Buhari Training Centre, Tanga Fresh Farms, SNV, Farm Friends Tanzania, MEDA, Agricare enterprises, and Marenga animal feeds. These collaborations had made farmers access to improved cattle breed, improved feeding techniques, and management.

4.4 Impacts of the capabilities acquired on dairy farmers and processors through contractual arrangements

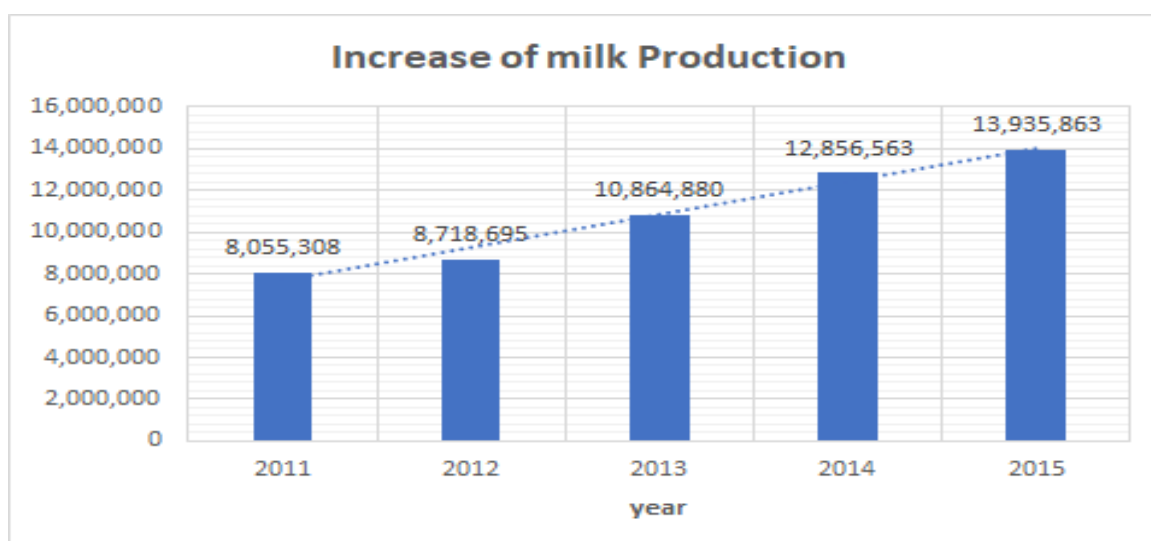
This part describes how the capabilities identified have been applied by farmers in terms of milk upgrading. A notable indicator of this is the frequency of milk rejection, statistics of milk production over the years, and trends of A. I use farmers, varieties of processed dairy products, and use of improved milk storage facilities.

Patterns of milk rejection-The acceptance of milk produced by meeting the standard required by the Tanga Fresh demonstrated improvements in capabilities among farmers. Farmers were asked to state the extent to which

their milk has been rejected as a result of failure to meet the standard required. About 20% said that they had not experienced any rejection, while 60% said their milk was only rejected on rare occasions. On the other hand, other 20% said their milk was only once rejected since they started the business.

Increase in milk production over the years- Improvement in dairy farming techniques has led to an increase in milk productivity and production quantities. The information obtained from TDCU showed that the milk production had increased from 8,055,308 liters in 2011 to 14,000,000 liters in 2015 as shown in Figure 3.

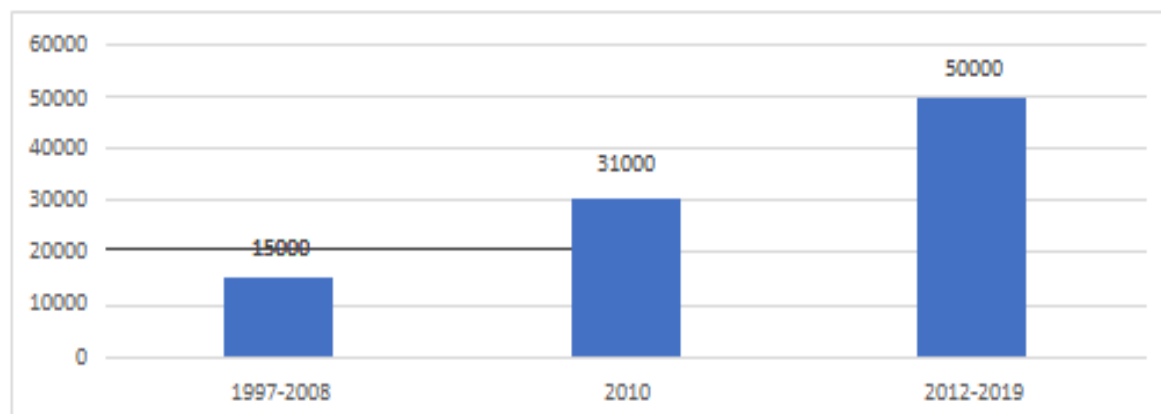
Figure 3: Increase in milk production



Source: TDCU Data, 2021.

Increase in milk processing in a day- The study found that the plant of Tanga Fresh Ltd. had acquired an expanded processing capacity from 15000 when it was launched to 31,000 in 2010. Between 2012 and the time this study was conducted in 2019 the processing capacity had grown and reached 50,000 liters of milk in a day, this is illustrated by figure 4.

Figure 4: Increase in milk processing in a day



Source: Tanga Fresh Data, 2021.

Use improved milk storage facilities- The study found that 64% of the farmers were using aluminum storage cans for storing milk, while 36% were still using plastic containers.

Tanga Fresh Ltd innovation capability -The study found that no major product innovations were introduced by Tanga Fresh Ltd but rather some minor improvements for the processed products. The study found that at a refrigerated temperature range of 5-7°C Tanga fresh milk has a shelf life of 7-9 days, the cultured milk and yogurt can stay for 28 days in the cold chain and long-life dairy products can stay for 6 months at a low temperature of the refrigerator. Other product lines by competitors including fruit-flavored yogurts are yet to be produced by Tanga Fresh Ltd.

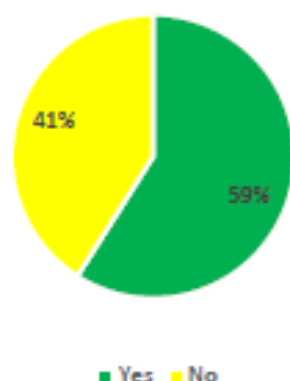
4.5 The System Declining Phase and the Challenges Encountered (Crises Phase)

The study has uncovered serious challenges confronting the system, and which threatens its continuity and sustainability. The analysis revealed challenges related to nature of the sectors engagement among Tanga Fresh Ltd, small dairy farmers and TDCU. Some of these challenges are described in the following paragraphs.

Expectations between dairy farmers, TDCU and Tanga Fresh Ltd were found to be mismatched, and thus resulting into several challenges. For instance, farmers expressed their feelings that TDCU is offering them a low and exploitative price for the high-quality milk they demand. In Muheza where the CHAWAMU cooperative serves, the milk is purchased at 723Tshs per 1 liter from farmers. For farmers, this price is not high enough to incentives the dairy farm expansion, and it is rather low given the rising feeding cost and disease treatments. As a result, some farmers decided to defy their primary cooperative and sell their milk into individual buyers and small business including hotels and cafeteria in town who are willing to offer them the price of Tsh 1200- 1500 per liter. The study encountered some farmers with a production capacity of 60 litres a day but they only supply 20 liters to TDCU to maintain their membership.

Farmers were also complaining about high interest rates and tough conditions for loans at FINCA bank loans. They added that although payment modalities are simple, there are delays in receipt of payments for their milk from TDCU and Tanga fresh Ltd (up to 10 days delays) that compromises their loan servicing capacity. Furthermore, farmers reported that when the system was established in 1985, there was a cattle credit system which encouraged farmers to join in dairy farming, but this program ended in 2005 with no plan to reintroduce it through TDCU or Tanga Fresh Ltd. As result, some farmers decided to deviate completely from dairy production to other industries/activities. This is reflected in the polarized view depicted on Figure 18 below where 41% of farmers said they were not satisfied with TDU and Tanga Fresh Ltd while 59% said they were satisfied.

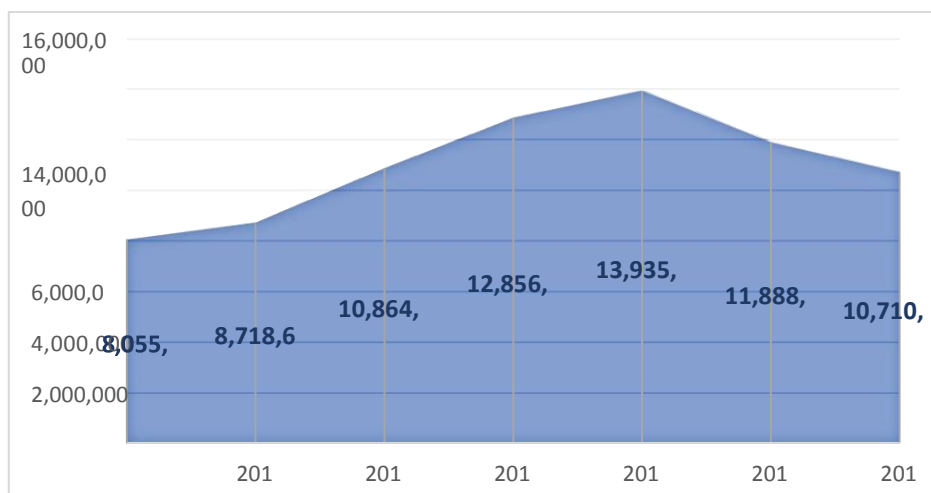
Figure 5: Farmers satisfaction with TDCU and tanga fresh Ltd



Source: Field Survey, 2021.

On the other hand, TDCU and Tanga Fresh Ltd was also dissatisfied with farmers' lack of trust, as they refuse to fulfill their commitments and sell only 35% of their milk to Tanga Fresh after receiving trainings, inputs, seminars and other forms of capacity building. This threatened the factory's performance, sustainability and contributed to a decline in production. The factory team added that, with an installation capacity of processing 150,000 litres a day, Tanga Fresh Ltd. Has been underutilized, as it processes only 50,000 litres on daily basis.

Figure 6: The decline in milk production from 2016 to 2017



Source: TDCU Data, 2021.

The study revealed that few farmers have managed to adopt the pure dairy breeds; this leaves a large proportion farmer keeping the local cattle i.e the African short horned Zebu which has a relatively lower milk production capacity. Artificial insemination is still poorly adapted by some dairy farmers. Instead, there is a widespread cross breeding involving the natural mating

practices. This is because some farmers could not afford the cost for artificial insemination. For some respondents, most of these challenges emerged after the TSDDP ended in 2005.

The dairy agro-industrial system in Tanga is considered to be under a threat by the New City Master Plan that limits cattle keeping in the city. TDCU, Tanga Fresh and Farmers contended that since Tanga dairy farming system is a peri-urban industry, it is threatened by the New City Master Plan. The fact that the system developments were initially excluded from regional development plans it caused disagreements between system managers and urban planners. As a result, some dairy farmers have started to reduce the number of dairy cows to comply with the New City Master Plan.

Other challenges are associated with emergence of micro-milk dairies such as Ammy Dairy that compete with Tanga Fresh Ltd for the raw milk to process. The study revealed that Ammy dairy pays 800Tsh per litre using weaker tests and lower standards as compared to Tanga Fesh Ltd with a more comprehensive milk testing procedure and an offer of 723 Tsh. The study noted that a large proportion of the milk rejected by Tanga Fresh LTD through TDCU is accepted by Ammy dairy.

Generally, it was found that the project's closure, which the Dutch government had sponsored from 1985 to 2005, was the primary cause of the challenges. It demonstrates that there was no plan in place for what would take place once the project was completed. The government expected that the system would continue to function once the project was finished. Unfortunately, the system became fragmented following the project's completion, and the government did not adequately support it with checks and balances.

5.0 Discussion

The discussion of these findings is based on the main research questions answered by the study, inquiring on the how did the Tanga dairy innovation system develop i.e. formation of linkages within the Tanga innovation system and the role played by such linkages in stimulating innovation among the smallholder dairy farmers and then why did the system fail.

To establish the understanding of approaches used to form and maintain linkages in The anga dairy-agro industrial innovation system formed, the study revealed that, the contractual arrangement (both formal and informal) in a combination of key player/intermediaries such as cooperatives played a key role in coordinating the various actors and their roles in the system (knowledge, financial resources, social capital, producers, processors). This allowed learning and sharing /exchange, and the use of dairy farming-related knowledge for economic relevance. These findings confirm those of a study by Leeuwis (2004) who argued that innovation is a result of an interactive learning

process from multiple actors through networking and linkages supported by the enabling environment.

The study revealed the prevalence of interactive learning, learning by doing involving the dairy farmers and other actors, in this case, the TDCU and Tanga Fresh Ltd. Such interactions forged the transfer of skills and knowledge dissemination for example through seminars, training, and collaborative projects. This approach has proven a high success rate, as farmers acquired capabilities to produce high-quality milk required by the processors. This recapitulates the work of Lundvall (1992) on interactive learning in the innovation system and its role in building the capability of weaker and particularly informal actors in the system.

One must acknowledge the importance of interrogating the extent to which such linkages contribute to the technological capability building among the smallholder dairy. As indicated in the previous section, contractual arrangements are very important for small-scale farmers to produce the high-quality products required by the processing firm. The researched dairy system demonstrated a significant technological capability building involving the small-scale farmers. This was achieved through their linkages and interactive learning with service providers, enforced quality standards, and other enabling agencies. Such arrangements stimulated capacity-building activities such as training and research field demonstrations targeting dairy farmers. The outcome a proper dairy feeding, use of A.I, use of improved dairy cows, record keeping, access to cattle credit, milk storage, and dairy management, and improved the capacity of farmers in milk-producing through the adoption of improved technologies. From the innovation system perspective, the relationships among the actors are important in building the technological capabilities of the farmers that would eventually raise productivity and at the same time support the development of processing firms.

These findings are also confirmed by Minot (1986) who observed that contractual arrangements influence productivity increase through “market specification”, “resource provision” and “production management”. Under the market specification, processors agree on the various attributes of the goods to be produced including the quality, timing, location, and price. At this stage, farmers have been informed of the standards related to production, product quality, and delivery as well as meeting any other quality requirements imposed by the processors. Regarding resource provision, the processor is compelled to offer the necessary inputs to the farmers.

In addition to the linkages roles in technological capability building among the smallholder dairy, this has been successful through the work of intermediaries. Against these positive findings, the informal nature of small farmers necessitates the intermediary players to be there. Intermediaries are vital in

influencing and connecting farmers, processors, extension officers, finance/credit providers, research institutes, and input suppliers beyond their contractual obligations. They allow information, material, technical support, credit flow, market access, and skills to flow across the system actors (FAO, 2013).

In this case, TDCU acts as an intermediary broker which, according to Winch and Courtney (2007) is “an organization acting as a member of a network of actors focused not only on the generation nor the implementation of innovations but also on enabling other actors to innovate”. The farmers benefit from TDCU as it takes the role of facilitator in arranging the actors to allow knowledge flow. For instance, by being the main player in the Tanga dairy system, TDCU has entered the contractual arrangements with potential supporting institutions like milk processors, input supplies, training, and research institutions. These institutions allow TDCU and its dairy farming members to access the various services and benefits. Such findings are complemented by Persson (2010) who found out that KAFAthe ME cooperative in Uganda had good contacts with agricultural input organizations and with training institutions such as NAADS (National Agricultural Advisory Services). The findings are also in line with Chrysa et al. (2012) who found that the Dutch agri-food innovation systems benefited from a wide array of brokers/intermediaries which function as facilitators by connecting demand and supply actors.

The Tanga Dairy System, on the other hand, is experiencing problems that still call for the implementation of critical plans, such as local competence building and inclusive planning for sustainable management. According to Lundvall et al. (2009), most African countries are still in the early stages of developing their innovation systems. Many new organizations, both formal and informal, depend on specific configurations to enable links and interactions that can last over time.

6.0 Conclusion, recommendations, and the way forward

The study concludes that formal and informal contractual arrangement remains the dominant approaches used in building linkages between smallholder farmers and industries in Tanga dairy innovation system. Based on this situation, the interactions between dairy farmers, the industry, and other actors were confirmed to be requisite for the dairy farmers’ acquisition of improved technologies and practices such as the adoption of zero-grazing, cross-breeding, access to inputs such as minerals, improved feeding practices, and disease control practices and thus improve socio-economic conditions to the dairy farmers and other system actors. Such findings confirm with configurations proposed under the Agricultural Innovation System (AIS)

framework, which emphasizes strong interactions among the key actors to enhance farmers' access to improved technologies.

The study concludes that enhancing the technological capability of Farmers is an imperative factor that should precede industrial development. Moreover, the coexistence and interdependence of different actors are necessary for industrial development. The case in point is the Tanga Dairy system whereby the back-and-forth interaction between smallholder dairy farmers and Tanga Fresh LTD has created a strong production system; whereby farmers were able to supply the needed quality and quantity of milk to Tanga Fresh for processing (forward linkages) in return for the technical support and credit flow from Tanga Fresh LTD (backward linkages).

The system, however, began to work poorly from 2016 to present. The output began to fall, and other actors decided to exit the system. The fundamental reason of this situation was the closure of the Dutch government-funded dairy development project, which supported the system's growth from 1985 to 2005. The government of Tanzania didn't have a plan in place for maintaining the system after the project was completed. It was assumed that the system would continue to work once the project was completed. Unfortunately, the system became fragmented due to a number of challenges following the project's completion, including a lack of confidence among system actors brought on by price differences, a failure to offer services such as cattle credit, payment delays, and internal disagreement among milk processors i.e. Tanga Fresh Ltd and Ammy Dairy.

Further investigation revealed that the system coordinator (TDCU) lacked the expertise required to deal with challenges that emerged within the system. Last but not least, the system was a peri-urban industry, whose developments were not included into Tanga City Master Plan (lack of inclusive and participatory planning). For instance, the New Tanga City Master Plan limited cattle keeping in the city. This resulted into disagreements between TDCU and City planners. Dairy farmers thus decreased the number of dairy cows to adhere to the New Tanga City Master Plan.

The discussion in this study has implications for both policy and theoretical developments in the field of innovation system research in the African context. In terms of theory, the study contributes to the conceptualization of factors contributing to the rise and decline of systems of innovation in Africa. In terms of policy, this paper suggests that since the growing of many innovation systems in Africa are backed by donors, it is crucial to put a plan in place, like local competence building and inclusive planning, to manage those systems in a sustainable way.

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Institutional quality and efficiency of smallholdings: Inferences from India's sectorial innovation system of natural rubber

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Abstract

The paper attempts to analyze the role of institutional quality at the micro level in determining efficiency outcome of the smallholdings in India's Sectoral Innovation System of Natural Rubber. The study used unit level data from Rubber Production Incentive Scheme of Government of Kerala, 2019 covering around 65000 RPS¹ member rubber growers. The study has found that efficiency outcome is not uniform across all RPS; with higher efficiency in high quality RPS operating villages as compared to low quality RPS operating villages. Hence, building institutions alone would not materialize the intended result; rather quality of institutions needs to be maintained for better efficiency outcome at the farm level.

Key Words: Innovation Systems, Institutional Quality, Efficiency

1. Introduction and the context

Despite comparatively low share of agriculture in Gross Value Added owing to the structural transformation (Kuznets & Murphy, 1966); larger absorption of labour along with inextricable nexus between "*the commodity problem*"² and "*the poverty problem*" places agriculture as a key sector, especially in the developing world. Undoubtedly, technological progress, irrespective of the sectoral dimensions, has been a powerful alternative to address the larger question of

“economic prosperity” and “the global poverty problem” (Schumpeter, 1934; Acemoglu, 2005; 2012; 2023; Acemoglu et al, 2021; De Janvry et al, 2000; De Janvry and Sadoulet, 2002; Mendola, 2003; 2007; Spielman et al, 2008; Awotide & Awoyemi, 2016; Awotide et al, 2016); as it has been a source of efficiency and increased material welfare (Coxhead and War, 1995; Edquist, 1997; Timmer and Los, 2005; Alston, 2010; Jorgenson, 2011). However, agricultural technology is far more complex that realization of its potential benefits depends not only upon technology by itself; but on farmers’ efforts to cop up with the uncertainties associated with climate (Otsuka and Kalirajan, 2008; Csaki, 1985); and instability in price in the open and integrated market regime (Rangachary et al, 2006). In the midst of these challenges, innovations; technological or institutional; have a key role to equip agriculture of developing economies in addressing their larger developmental questions (Spielman, 2005).

In India, though agriculture contributes hardly 17 per cent to its Gross Value Added at Basic Prices (Govt. of India, 2023)³; it remains as the primary livelihood opportunity for 55 per cent of its work force (Registrar General and Census Commissioner of India, 2011)⁴. Within agriculture, plantation agriculture has been historically promoted as a foreign exchange earner in India with a few exception of import substituting crops like Natural Rubber (Joseph and George, 2010). In these lines, plantation sector has been able to attract attention of the state in terms of innovation policies. This resulted in a series of institutional innovations in the sphere of production and marketing mainly for raising international competitiveness (Joseph and George, 2010). Setting up of Commodity Boards and the legislations for empowering them like Rubber Act in the case of Natural Rubber; and grass root level institutional innovations like Rubber Producers’ Society (hereafter RPS) have been the leading initiatives in this regard⁵.

In the past, Natural Rubber sector was dominated by large estate owners (George and Tharakan, 1985); but currently majority of the cultivators belong to small holders⁶ (Joseph and George, 2010, Rubber Board, 2020). Hence, performance of the sector in general and fortunes of its small holders in particular decisively depend upon how effectively they manage the crop subject to given market conditions. The fact that among all plantation crops, Natural Rubber belongs to the category of crops which experienced high price instabilities in the post reform period as compared to the pre-reform regime of protection and market interventions⁷; makes the natural rubber production sector more vulnerable to conditions in the market. Along with unstable prices, augmenting cost of cultivation and cost of harvesting owing to acute tapping labour shortage poses further challenge to the sector; which depends largely upon labour for harvesting (Viswanathan, 2013; Siju et al, 2015; George and Chandy, 2015). In this changed scenario, performance of the plantation sector; particularly the Natural Rubber sector depends on how effectively small

holders are able to withstand the adverse consequences of instability in price; and how innovative are they with respect to managing their crop and enhancing productive efficiency at the farm level; especially during adverse movements in prices. Thus, it comes out that as price is exogenous to the system and decided by the invisible hands in the deregulated open market regime, livelihood outcome of the smallholders needs to be addressed by ensuring efficiency in the overall management of the crop, in which innovations of different kinds; both technical and institutional; are expected to play a key role.

Hence, institutional innovations are expected to create significant impact upon efficiency outcome at the farm level; as institutions⁸ primarily aim to promote co-operative behaviour and networking; and thereby incentivize all the actors in the innovation system (Edquist and Johnson, 1997). Hence, it follows that when the sector is faced with exogenous disincentive factors like adverse prices, institution has to play its key role of incentivizing the farmers to maintain the operation of the crop intact. In this backdrop, the paper aims to address the question how efficiency outcome of smallholders is effectively addressed by the institutional domain at the grass root level of the sectoral innovation system of the respective crop under consideration, Natural Rubber. While significant works have already been done both theoretically and empirically incorporating institutional factors at the national level within the national and sectoral system of innovation perspective (Lundvall et al, 1988; Lundvall, 1992; 1998; 2007; 2008; 2010; 2022; Malerba, 2002; Johnson et al, 2004; Arocena and Sutz, 2000; Lee and Park, 2006; Li et al, 2011; Ockwell and Byrne, 2016; Balzat, 2002; Edquist and Hommen, 2008; Edquist, 2001; Castellacci and Natera, 2013; Rakas and Hain, 2019) empirical studies at the micro level focusing institutions at the grass root level are found to be less in the literature (Breschi Lissoni, 2001; Asheim et al, 2006; Wing and Wood, 1995; Asheim et al, 2011); especially in the developing country context like India. The paper aims to fill this gap in the literature. The paper is structured in five sections including the introduction and context. The second section provides the theoretical framework for setting the analytical background for the paper. The third section details the methodology of the study. The fourth section deals with institutional quality and efficiency outcome at the farm level and final section concludes the entire discussion with a note on few policy concerns.

2. Theoretical framework

Innovation System framework⁹, whether it is national, regional, sectoral or technological, is useful in empirical study of innovations in their larger or specific local context (Edquist, 1997). The conceptual trajectory of the innovation system framework can be tracked as contributions in National System of Innovations (Lundvall, 1992; Freeman, 1995) to the Sectoral System of innovation and production, which is restricted to one sector of production

(Nelson and Rosenberg, 1993; Malerba, 2002; Edquist, 1997; Malerba and Mani, 2009); say agriculture or a crop like Natural Rubber. This development in the analytical framework could be seen as a result of the need for incorporating the role of specific institutions at the sectoral level so as to make the innovation system framework theoretically strong (Edquist, 1997). Analysis of system of innovation at the sectoral level could incorporate the sector specific as well as national institutions affecting the outcome of the given sector under analysis (Edquist, 1997). It has also been felt that because of greater international integration of the economies with globalization, innovation system analysis at the sectoral level by incorporating sector specific institutions and national and international institutions pertaining to the given sector would increase the utility and strength of the framework (Lundvall, 1992). These developments throw light on the fact that innovation system has been conceptualized as an institutional economics construct (Edquist 1997; Nelson and Nelson, 2002). The “institutional set up” along with the “production structure” is considered as one of the main building blocks of innovation system approach at all its analytical levels (Lundvall, 1992; Edquist, 1997; Nelson and Nelson, 2002).

In the innovation system framework co-operative behavior¹⁰ among agents is given due significance, which is conditioned by the underlying institutional or organizational framework. The behaviour of firms (farming households)¹¹ or innovating agents is shaped by the underlying institutions as constraints or incentives for innovative performance (Edquist, 1997). Institutions are assigned a greater role in facilitating flow of information within the system (Clark, 2002; Lundvall, 2007). When the system is with greater amount of raw information, the system becomes more chaotic and internal organisations or institutions should give its components their intended meaning and make it economically productive information (Clark, 2002). The fact that information flow assumes its value only when the sender and the receiver have deep and shared understanding of the shared information, market for information may not function efficiently and would lead to asymmetric information between them. Hence, the underlying organizational and institutional set up is expected to fill this gap for better knowledge flow and its economic utilization (Clark, 2002).

Productive information flow depends crucially upon the actions on the part of recipients as well in terms of its investment in knowledge (creation and absorption). In the manufacturing sector since firms have better in house R & D, utilization of knowledge could be better possible. But when it comes to agriculture sector, farmers’ utilization of knowledge is severely constrained by this large requirement of knowledge investment, which needs to be supported by the organizational or institutional set up of the system (Spielman, 2005; Spielman and Birner, 2008; Spielman and Kelemework, 2009; Spielman et al, 2011). This necessitates the formation of well organized and co-operative knowledge transfer mechanism by minimizing the cost of information search

and maximizing the receptivity of knowledge users. This interactive nature of knowledge provides the foundation for innovation system perspective which decides whether the system is effective or ineffective in terms of its outcome (Clark, 2002). The system should permit information interchange among agents or nodes for contributing to innovation and change leading to better developmental outcomes. Hence, the underlying institutions should be proactive for promoting co-operation and innovative behaviour within the system. Innovation system literature also argues that institutions should create a proactive incentive structure as well for promoting co-operative arrangements among actors that currently act as rivals rather than as potential sources of new knowledge (Clark, 2002).

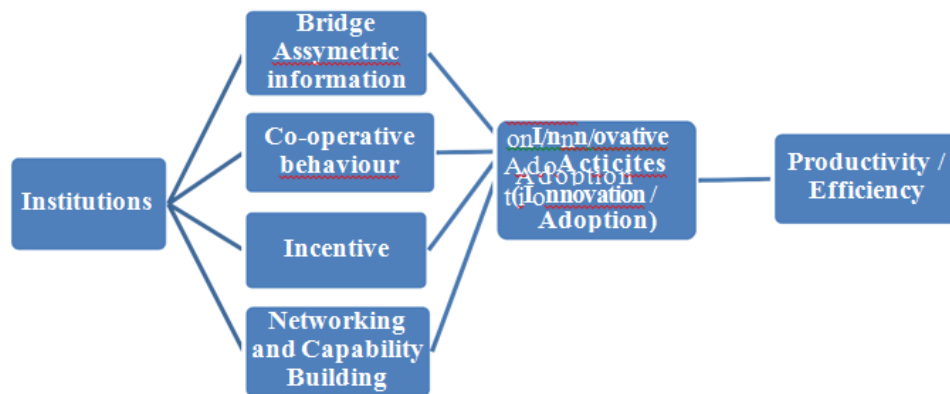
This approach gives more emphasis not only to the creation of knowledge but to the factors determining the demand for and use of knowledge in innovative ways as well. Innovation system approach particularly Agricultural Innovation System Approach is found to be more holistic than the earlier models in which private sector agents do play a crucial role along with the enabling environment like policies and institutions (World Bank, 2006). In effect institutions¹² determine the efficiency and stability of cooperation and competition among agents by influencing their ability to interact for generating, diffusing and utilizing the knowledge (Spielman, 2005). Hence, in some of the studies, focus with regard to “institutions” shifts from the public sector research institutions to “the rules of the games” in the innovation system framework (Spielman, 2010). The institutional factors or enabling and disabling conditions in the innovation system determines to a larger extent the performance of any innovation system (Klerkx et al, 2005; World Bank, 2012).

Institutions can be a limiting factor as well by limiting the network among actors. Institutional failures both hard and soft¹³ can impeditment the performance of the system (Knickel et al, 2009). When network failures occur with actors are being locked in the existing network and cannot accept ideas of their own or from outside, it becomes institutional failure. As said earlier, the role of institutions in innovation system depends upon the interaction possibility between or among actors at different levels. It could be at the level of the firm (farmer household) or at the level of the market or the system at the macro level. At the level of the market interactions could be expected between or among firms (farmer households), between or among firms (farmer households) and various organisations which has been consciously created or evolved spontaneously within the system (Lundvall, 2007). Interactions are also expected between or among firms (farmer households) and the knowledge infrastructure.

Innovation system framework with institutional approach also how context and its evolution make differences in interactions and learning (Johnson et al, 2004). Neoclassical economics with its global rationality of profit maximization

sticks to a general rule of interaction, which is independent of time and space (Johnson et al, 2004). Hence, Institutions are expected to reduce uncertainty involved in the innovative activities (both creation and its adoption at the farm level) by providing information and thereby managing the possibility of asymmetric information between the developer and the user of an innovation or creative idea (Edquist and Johnson, 1997; Johnson et al, 2004). Institutions in a way reduce the informational and computational burden of the so called rational economic man via providing information or reduce the need for actors to gather them (Williamson, 2000; North, 1990; 1991). Hence, institutions enable the actors to efficiently address the issue of transaction cost, which is expected to bring an efficient outcome in terms of productive or technical efficiency and distributive efficiency (North, 1990).

Figure 1: Framework of innovation, institutions and efficiency



Source: Adapted from Edquist and Johnson, 1997

Institutions are also expected to manage conflicts among actors in the innovation system. Institutions control opportunist behaviour among actors being rational self interested agents to take undue advantage of the information asymmetry in the system (Williamson, 2000; Groenewegen et al, 2010). Another significant function of institution is to provide incentives to the actors to perform innovative activities (either to create an idea or to put it in use or adopt it). Incentives undoubtedly will help the innovation actors to take risk and deal with the uncertainties involved in the innovation process¹⁴. The incentives could be of a pecuniary like subsidy, tax benefits, wages and salary scheme etc. or non-pecuniary nature like ensuring right over novelty in the form of patents, trademarks etc. (North, 1990; Edquist and Johnson, 1997).

Hence, institutions create better efficiency outcome in the innovation system by bridging asymmetric information among actors, promoting co-operative behaviour and networking and interactive learning among actors and incentivizing the actors especially during crisis times (see Edquist and Johnson, 1997 in figure 1). It also comes out that better institution facilitate efficient

knowledge sharing, promote co-operative behaviour, bridge asymmetric information regarding technical knowledge; and hence promote better efficiency outcomes at the grass root level. Thus, institutional quality would be a significant variable which is expected to impact upon the efficiency outcome at the farm level; as farmers associated with better functioning or quality institution will have better efficiency outcome. The paper addresses this broader theoretical question; whether institutional quality matters for efficiency outcome at the micro level keeping “institutions as organisations” at the backdrop; in the sectoral agricultural innovation system perspective.

3. Methodology of the study

3.1 Choice of the sectoral system of innovation and fixing the boundary

The study takes sectoral innovation system of Natural Rubber as the case for investigation. The innovation system of Natural Rubber had been acclaimed as one of the best performing innovation systems having a strong institutional architecture with R & D driven output and productivity enhancement (Joseph and George, 2010; Mani and Santhakumar, 2011). Apart from that Natural Rubber being a strategic industrial raw material (Cornish, 2017); assumes a lot to the developmental requirements of an economy like India (Joseph et al, 2018). In the changed scenario of heightened price instability the way in which the system behaves is a question of interest; and exploring the nuances of which is of both academic and policy interest. The boundary of the innovation system is fixed by keeping the question being addressed at the backdrop. Interaction among farmers, farmer to the knowledge infrastructure and the organizational entities like Rubber Board and other companies is facilitated through the grass root level institution, RPS. Hence, the boundary is fixed within the limits of interactions in the production sector by keeping farmers or smallholders at the centre of innovation system for analyzing efficiency outcome at the farm level.

3.2 Classification of agro-climatic regions

We use the latest classification of agro-climatic regions of Natural Rubber cultivation in Kerala based on districts by the Rubber Research Institute of India (Veeraputhran et al, 2013). The information on district available in RPIS data is used for the purpose of classification. The state of Kerala is renowned to be the dominant traditional region of natural rubber cultivation in the country and the state has been classified into 4 agro climatic regions using districts having similar climatic conditions for rubber cultivation by the Rubber Research Institute of India – Northern zone, North central zone, Central zone and Southern zone (Veeraputhran et al, 2013)¹⁵.

3.3 Data source and variable construction

The study relies on the unit level data generated from the Rubber Production Incentive Scheme by the Govt. of Kerala¹⁶ for the period of 2018-19 at the farm level covering around 65000 farmers in the state of Kerala, probably the largest unit level data in the Natural Rubber sector. In the RPIS data, information has been available at three digit disaggregated level – District, Taluk and Village. Tapped area applied for the benefit of subsidy is approximated to actual tapped area, which is the best proxy from the RPIS data for the actual tapped area; since whole of the area tapped might have been applied for the subsidy benefit; as majority of the rubber growers are small holders (Rubber Board, 2020). Sale of Natural Rubber for the period is approximated as production for the period; as majority of the producers are smallholders; and hence stock holding behaviour at the farm level would be negligible. Since area under cultivation is not available from the data at the unit level, tappable area is approximated as the size of holdings. Untapped area is derived by deducting tapped area from the tappable area.

Productivity is used as proxy variable for efficiency outcome at the farm level. Since we have no data on capital and labour, technical efficiency measures are not possible from the data. Since approximate tapped area is available from the data, per hectare productivity would serve our purpose of efficiency estimation. Apart from that cultivation of a crop like Natural Rubber involving larger opportunity cost in terms of allocation of land for a longer period of time necessitates representation of efficiency with respect to land from the farmer's point of view. Hence, our definition of efficiency is efficiency of the land with respect to productivity per hectare of land. Productivity is measured as output per hectare at the unit level using the usual methodology of measurement, notwithstanding the possible limitations due to the proxies. Data on sales, which is approximated as production for the period of the farming unit is divided by the tapped area applied for subsidy, which is approximated as actual tapped area for the same year.

Density of plants is an important variable influencing the efficiency outcome at the farm level, since it has significant impact upon growth of the plants, incidence of panel diseases and yield (Leong and Yoon, 1982; Veeraputhran et al, 2013). Since only data on matured trees is available from RPIS data, density of matured plants is worked out as a ratio of number of matured trees to the tappable area, which would serve our purpose. This variable can indirectly capture the destruction of trees after planting and the farms where planting is done more than the optimum limit suggested by the Rubber Board¹⁷.

Model RPS scheme was launched in 1999-00, with an objective of overall efficiency improvement in the production sector; and around 35 Model RPS were formed at the national level, out of which 29 Model RPS were formed in

Kerala. Operational village of all of them were identified from the list of Model RPS as of now except 1 in Ernakulam district. The operational village of the model RPS was gathered from the RPIS website of Government of Kerala using the RPS locator option. Using the details of village in the RPIS data, a model RPS dummy has been created with 1 for model RPS functioning villages and 0 for other RPS villages.

Institutional quality variables are identified by using the details of grading of RPS (A, B, C and D grade) by the Rubber Board available from the RPS Database of the Rubber Board. This grading could be taken as a proxy for the quality of the operation of RPS as it could be inferred from the table A1.1 in Appendix I. The classification criterion by the Rubber Board satisfies some of the innovation system dimensions in the domain of (1) infrastructure, (Smith, 1997; Klerkx et al, 2012) (2) innovation capability building, (Hall, 2005; Hall et al, 2002; Hall, 2007; Spielman, 2008) (3) knowledge, information and networking (Spielman and Birner, 2008; Klerkx et al, 2012) and (4) bridging institution (Spielman and Birner, 2008). A grade RPS seems to be high quality RPS having activities in all the innovation system dimensions as compared to B, C and D Grade. In the infrastructure dimension, A grade RPS will have facilities like Group Processing Centre (GPC) with computer and other accessories, latex collection centre, input depots with rubber procurement and an own office building. RPS with B grade will have latex collection centre and input depots and the office building will be either rented or own. RPS with C and D grade will not have any of these infrastructure facilities.

In the innovation capability building domain, while A-grade RPS conducts agro-management training, SHG activities, capacity building programmes for tappers and growers and apiculture, B, C and D grade RPS has no such activities. In the Knowledge, Information and in networking Domain, A-grade RPS members normally sit together in 4 general body meetings including 1 annual general body meeting, 8 to 12 executive committee meetings. In addition to the mandatory meetings, A-grade RPS also conducts seminars and workshops on innovative themes of farming interest. RPS conducting around 2 to 3 general body meeting and 5 to 8 executive committee meetings are categorized as B grade RPS. RPS conducting only 1 general body meeting and 4 executive committee meetings are classified as C-grade RPS and RPS with no meeting at all are categorized as D-grade RPS. In the bridging institutions domain, only A-grade RPS has linkage with Rubber Board, knowledge infrastructure RPS promoted companies as compared to all other categories. A-grade RPS submits up to date audit report to the Rubber Board, for B grade RPS audit report is pending for one year. If audit report is pending for 2 years it becomes C-grade RPS and if it is unduly pending for indefinite period it falls into D grade RPS.

RPS institutions, mostly defunct and not performing any of the listed activities and functioning only for having subsidy under RPIS scheme are classified as D grade RPS. Based on the parameters cited in table A1.1 in Appendix I, A-grade RPS could be considered as high quality RPS followed by B, C and D. It could also be identified that no significant difference could be identified between C and D grade RPS in features. Hence a three-fold classification as high quality (A-grade RPS), medium quality (B-grade RPS) and low quality RPS institution (C and D-grade RPS) would make our analysis more meaningful. In the RPS database along with grade of RPS details of their village of operation is also available and the same is used for giving grade for villages in the RPIS data. Hence, we could identify the quality dimension of RPS at the village level and three dummy variables for capturing the effect of three groups of RPS institutions upon farm level efficiency have been created for our estimation purpose.

As categories of adopters would also have implications on efficiency outcome at the farm level, dummy variables representing category of adopters are also included in the analysis. Using year of adoption in the data, adopters of high yielding variety clones are grouped into different categories using the standard methodology suggested by Roger, 1961; 2010.¹⁸ The analysis has been done by considering high yielding variety clones as one group and not separately for RR11 105 and RR11 400 series, as number of observations of RR11 400 series has been found to be not sufficient for adopting the classification as compared to RR11 105.

Cost of harvesting is also incorporated in analysis as it would impact upon efficiency outcome at the farm level. This has been constructed as agro-climatic region based dummy variable using the information available from the census report of rubber tappers published in 2016 by the Rubber Research Institute of India. Average cost of harvesting is available across 4 agro-climatic regions, which is the piece rate of harvesting for male tappers (rupees per hundred trees). Central had the highest cost of harvesting (Rs. 157.3 per 100 trees) followed by north (Rs. 154.4 per 100 trees), north central (Rs. 134.4 per 100 trees) and the south (Rs. 131.2 per 100 trees). The difference seems to be significant across all regions as well. Hence, we could think of four dummy variables for cost of harvesting and we use high cost dummy for our estimation purpose.

3.4 Estimation procedure

Testing the overall significance of average productivity differences across quality dimension of RPS institution is carried out with One-way ANOVA and the individual mean differences across all possible groups have been performed with Post-hoc test (Multiple Comparison Test) using Games-Howell methodology, which does not require equal variance assumption. Regression

model has been estimated using OLS procedure with productivity of natural rubber as dependent variable and two institutional quality dummy variables, one representing low quality institutions (IQ _ Dummy _ Low) and the other representing high quality institutions (IQ _ Dummy _ High), along with other variables identified from the existing studies as explanatory variables. The model would be specified as follows;

$$Y_i = \alpha_1 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + U_i;$$

Where;

Y_i = Ln _ Productivity of Natural Rubber

X_1 = IQ _ Dummy _ Low

X_2 = IQ _ Dummy _ High

X_3 = Model RPS _ Dummy

X_4 = Ln _ Density of Matured Plants

X_5 = Agro _ Dummy _ North South

X_6 = HYV Clone _ Dummy

X_7 = Ln _ Untapped Area

X_8 = Cost of Harvesting _ Dummy

X_9 = Laggards _ Dummy_1

X_{10} = Late Majority _ Dummy_2

4. Institutional quality and efficiency outcome: Micro level inferences

Before entering into the modeling exercise, average productivity is estimated across quality of RPS at the aggregated and disaggregated level; across agro-climatic regions; and reported in table 1. Average productivity is found to be higher in the high quality RPS operating villages as compared to medium and low quality RPS operating villages at the aggregate level. This is in conformity with our theoretical expectation that higher the institutional quality higher the efficiency outcome in terms of productivity at the farm level. While the average productivity in the high quality RPS operating villages is to the extent of 1002.2 kg / hectare, average productivity in the medium quality RPS operating villages is lower than the high quality operating villages (961.1 kg per hectare). Productivity further declines to 892.6 kg / hectare in the low quality RPS operating villages. Hence, productivity or efficiency outcome augments with improvement in the quality of the institution at the grass root level. The results of one way ANOVA and post-hoc test in table 2 indicate that all possible mean differences at the aggregate level are statistically significant at 1 per cent level.

The same pattern could be observed at the disaggregated level as well. In the northern zone, average productivity is found to be the highest in the high quality RPS operating villages (1010.7 kg / hectare); followed by median quality RPS (938.4 kg / hectare) and low quality RPS operating villages (886.8

kg / hectare). All possible mean differences in the northern zone are also significant at 1 per cent level as it could be inferred from the results of one way ANOVA and post-hoc test in table 2. In the north central zone, in high quality RPS operating villages, average productivity is to the tune of 1040.9 kg / hectare followed by medium quality RPS operating villages (1015.2 kg / hectare) and low quality RPS operating villages (988.8 kg / hectare). Difference in average productivity between low quality and high quality RPS operating villages has been found to be statistically significant; but however, statistically insignificant between low quality RPS operating villages and medium quality RPS operating villages. Similarly, average productivity between medium quality RPS operating villages and high quality RPS villages is also not statistically significant (refer to table 2). This would probably because of the reason that north central region currently is one of the highly productive regions (refer to table 1) and hence medium quality RPS operating villages would be irrelevant and only high and low quality RPS operating villages operate. Hence the experience of the north central region would go along with our theoretical expectation regarding quality of the institution and efficiency outcome at the grass root level.

Table 1: Average productivity of natural rubber across quality of rps institutions

Quality of RPS	Number	Mean	Median	SD	CV
Northern Zone					
Low Quality RPS	7483	886.8	800.0	541.7	61.1
Medium Quality RPS	11527	938.4	858.0	567.1	60.4
High Quality RPS	4795	1010.7	911.4	631.1	62.4
Total	23805	936.8	851.1	574.5	61.3
North Central Zone					
Low Quality RPS	2300	988.8	903.7	610.1	61.7
Medium Quality RPS	3303	1015.2	918.6	629.0	62.0
High Quality RPS	2593	1040.9	933.3	647.9	62.2
Total	8196	1015.9	920.1	630.1	62.0
Central Zone					
Low Quality RPS	5997	801.4	687.7	549.6	68.6
Medium Quality RPS	5643	833.8	729.7	552.1	66.2
High Quality RPS	3193	836.6	750.0	541.4	64.7
Total	14833	821.3	715.0	549.0	66.9
Southern Zone					
Low Quality RPS	3021	1015.5	864.7	713.1	70.2
Medium Quality RPS	5270	1112.1	1000.0	698.6	62.8
High Quality RPS	3428	1115.8	982.6	748.6	67.1
Total	11719	1088.3	962.0	718.5	66.0
All Kerala					
Low Quality RPS	18795	892.6	781.3	588.6	65.9
Medium Quality RPS	25761	961.1	864.4	608.5	63.3
High Quality RPS	13997	1002.2	897.5	654.1	65.3
Total	58553	948.9	846.3	614.9	64.8

Source: Estimated from Rubber Production Incentive Scheme Data, 2019

The general pattern of higher productivity in the high quality RPS operating villages and low productivity in the low quality RPS operating villages could also be observed in the central and southern region as well. In the central region average productivity is found to be the highest in the high quality RPS operating villages (836.6 kg / hectare) as compared to the medium quality (833.8 kg / hectare) and low quality RPS operating villages (801.4 kg / hectare). All mean differences are statistically significant except the difference between medium quality RPS operating villages and high quality RPS operating villages (refer to table 2).

Table 2: One-way ANOVA and post-hoc test (games – howell) for significance of group mean differences

(I) Quality of RPS	(J) Quality of RPS	Mean Difference (I-J)	Std. Error	Sig.	
Northern Zone					
Low Quality RPS	Medium Quality RPS	-51.6	8.2	0.000	***
Low Quality	High Quality RPS	-123.9	11.1	0.000	***
Medium Quality	High Quality	-72.3	10.5	0.000	***
F Value			68.4	0.000	***
North Central Zone					
Low Quality RPS	Medium Quality RPS	-26.4	16.7	0.258	
Low Quality	High Quality RPS	-52.1	17.9	0.011	**
Medium Quality	High Quality	-25.7	16.7	0.276	
F Value			4.17	0.015	**
Central Zone					
Low Quality RPS	Medium Quality RPS	-32.4	10.2	0.004	***
Low Quality	High Quality RPS	-35.2	11.9	0.009	***
Medium Quality	High Quality	-2.8	12.1	0.971	
F Value			6.63	0.001	***
Southern Zone					
Low Quality RPS	Medium Quality RPS	-96.7	16.2	0.000	***
Low Quality	High Quality RPS	-100.3	18.2	0.000	***
Medium Quality	High Quality	-3.6	16.0	0.972	
F Value			21.0	0.000	***
All Kerala					
Low Quality RPS	Medium Quality RPS	-68.5	5.7	0.000	***
Low Quality	High Quality RPS	-109.6	6.9	0.000	***
Medium Quality	High Quality	-41.1	6.7	0.000	***
F Value			137.1	0.000	***

Source: Estimated from Rubber Production Incentive Scheme Data, 2019

As it has been observed in the case of central region, all mean differences are statistically significant in the southern region as well, except the difference in average productivity between medium quality RPS operating villages and high

quality RPS operating villages (refer to table 2). Hence, the experience of southern zone also reveals that institutional quality matters for efficiency outcome at the farm level as in the case of other three agro-climatic regions.

This has been followed by estimation using OLS regression model¹⁹ with institutional quality variables along with other possible determinants at the aggregate level and reported in table 3 (refer to table A1.2 in Appendix I for Summary Statistics); after converting all ratio variables in logs to deal with possible outliers. The estimated overall model is found to be statistically significant at 1 per cent level as t could be inferred from the F statistic and adjusted R -squared value has been found to be close to 0.125. The model has no issues of serial correlation as Durbin-Watson statistic is close to 2. Residuals are also found to be approximately normal as it could be seen from the histogram of regression standardised residual and the normal p-p plot of regression standardised residuals (refer to figure A1.1 in Appendix I). No issue of multi-collinearity is found as Variance Inflation Factors for all variables are within the admissible limit (refer to table A1.3 in Appendix I).

Farms with higher density of matured plants are found to be having better productivity as compared to farms with lesser density of matured plants. This throws light on the need for maintaining the farm in tact with optimal density matured plants. Though this result seems to be quite expected, it leads us to the inference that destruction of plants would be a serious issue in many fields, which needs to be addressed. It has also been found that fields with more untapped have comparatively lesser productivity, which necessitates that untapped area is a serious concern and to be controlled for raising the productivity of natural rubber. This would be probably because of the reason that larger holdings leave their area more untapped than the smaller holdings because of the adverse cost conditions and the uncertainties owing to instability in prices. This throws light on two things; firstly, policy initiatives should be made to harness the untapped area with larger holdings either by incentivizing the farmers to tap the trees at the optimum level through institutional interventions. Secondly, institutions should also do a pro-active role in harnessing the untapped area by taking a lead role. It comes out from the fact that inactive RPS²⁰ in many regions could also be a reason for higher untapped area in larger holdings and energizing RPS by converting medium quality RPS into high quality could solve the issue to some extent.

Table 3: Heteroskedasticity-corrected Model Dependent variable: Ln _ Productivity

<i>Variables</i>	<i>Coefficient</i>	<i>t-ratio</i>	<i>p-value</i>
Constant	4.548	65.70	0.000 ***
	(0.069)		
IQ _ Dummy _ Low	-0.061	-9.34	0.000 ***
	(0.007)		
IQ _ Dummy _ High	0.050	7.02	0.000 ***
	(0.007)		
Model RPS _ Dummy	-0.040	-4.15	0.000 ***
	(0.010)		
Ln _ Density of Matured Plants	0.599	54.63	0.000 ***
	(0.011)		
Ln _ Untapped Area	-0.163	-35.71	0.000 ***
	(0.005)		
HYV Clone _ Dummy	0.041	1.58	0.113
	(0.026)		
Agro _ Dummy _ North-South	-0.096	-12.66	0.000 ***
	(0.008)		
Cost of Harvesting _ Dummy	-0.050	-5.48	0.000 ***
	(0.009)		
Laggards _ Dummy_1	0.019	2.39	0.016 **
	(0.008)		
Late Majority _ Dummy_2	0.022	3.39	0.001 ***
	(0.007)		
	Statistic	P Value	
F (10, 55500)	784.58	0.000	***
Adj. R-Squared	0.125		
D.W	1.894		
N ²¹²¹	55511		

Note: Figures in parenthesis are standard errors

Source: Estimated from Rubber Production Incentive Scheme Data, 2019

Dummy variable for north and south is found to be significant with north having comparatively better productivity than the south. This would be probably because of much lower productivity in the central region as compared to all other regions, though southern region has better productivity (refer to table 1). Cost of harvesting is found to be having negative impact upon productivity at the farm level as expected. Hence, productivity is higher in agro-climatic regions with lower cost of harvesting and vice versa. This throws light on the issue of tapping labour shortage in the natural rubber sector, which is so acute in some of the agro-climatic regions like central region. It gives the impression that policy interventions to address tapping labour shortage seems

to be one area where innovation has to take place; notwithstanding the fact that there were initiatives in the past like Rubber Tappers Bank to address the issue. HYV clone dummy variable is found to be statistically insignificant in the model implying that there is no significant difference in productivity between RRII 105 and RRII 400 series at the aggregate level. This is against the claim that RRII 400 series is highly productive than RRII 105. This requires detailed investigation which is beyond the scope of the present paper. Laggards and late majority adopters are found to be having higher productivity as compared to other category of adopters including early adopters and innovators as against our theoretical expectations. However, age of the plant is an interacting factor and the result is not concrete; hence requiring detailed enquiry. Productivity in model RPS villages is found to be less than that of the ordinary RPS villages, which leads us to the inference that Model RPS scheme once successful could not sustain by itself and poses the question on the sustainability of the sponsored institutions, requiring detailed investigation within the sectoral innovation system of natural rubber.

Finally, Institutional quality dummy variables for low quality RPS operating villages and high quality RPS operating villages are the variables of our interest in the model with respect to institutions. Both the dummies are found to be statistically significant at 1 per cent level. The parameter values for low quality RPS operating villages and high quality RPS operating villages are found to be -0.061 and 0.050 respectively, which leads us to the inference that in low quality RPS operating villages, productivity is lower as compared to medium and high quality operating villages. Similarly, productivity is higher in high quality operating villages as compared to both medium and low quality operating villages. Hence, higher productivity is associated with high quality institution and vice versa, which leads us to the conclusion that institutional quality does matter for efficiency outcome at the farm level.

5. Discussions of the results and policy concerns

The present enquiry aimed to look at the role of institutional factors at the grass root level in determining efficiency outcome at the farm level within the framework of sectoral agricultural innovation system of natural rubber. The study has been guided by the hypothesis that institutional innovation enhances efficiency outcome of the smallholders at the micro level. The study leads us to the inference that institutional factors have unclenching influence upon the efficiency outcome at the farm level. It has been observed that villages with high quality RPS are having better productivity than the medium and low quality RPS operating villages both at the aggregate and disaggregated level. However, higher productivity is observed in ordinary RPS operating villages as compared to model RPS operating villages. It implies that model RPS once successful could not sustain over time and poses the question on the sustainability of sponsored institutions in the long run.

Estimation results confirm that farms with higher density of matured plants are with higher productivity and vice versa. It leads us to the observation that majority of the farms are with less than optimum size of matured plants and plant destruction at the farm level needs to be properly addressed through appropriate institutional interventions. Untapped area is also a serious concern and policy initiatives are required to harness the untapped area with larger holdings either by incentivizing the farmers to tap the trees at the optimum level through appropriate institutional interventions. Hence, micro level planning is required to address the issue, for which institutions at the grass root level like RPS should be empowered to perform a proactive role. Apart from that the schemes implemented to reduce the untapped area like adoption of farms needs to be evaluated timely for addressing the issue. Larger size of holdings needs to be targeted to reduce the gravity of the issue as the size of untapped areas will be probably higher for higher size of holdings.

No significant difference in productivity between RR II 105 and RR II 400 series could be found from the estimation results and efficiency outcome is found to be better for laggards and later adopters as compared to innovators and early adopters, which would be probably because of higher aged plants in the innovators' and early adopters' field and also due to larger size of holdings for the early adopters as compared to the later adopters. Productivity is found to be lower in the agro-climatic regions with high cost of harvesting, which throws light on the need to address the issue of tapping labour shortage in the natural rubber sector, which is acute in all regions especially in the central region. This would be an area where innovation has yet to take place; though there were initiatives in the past like Rubber Tappers Bank to address the issue.

5.1 Policy concerns

In lieu of conclusion, the story of natural rubber in the Indian context reveals that institutional quality matters for efficiency outcome at the micro level. It leads us to the inference that building institutions at the grass root level alone will not lead to the intended outcome; rather efforts to maintain quality of institutions needs to be given thrust in the policies. It has also been observed that potentiality of raising efficiency at the farm level is immense in the natural rubber sector by upgrading low quality to medium quality and from medium quality to high quality RPS at the aggregate as well as at the disaggregated level. The study would also suggest a few areas where proactive institutional interventions could create positive changes. Larger untapped area along with less than optimal density of matured plants in many holdings owing to destruction of plants or less care at farm level especially during adverse prices; and low productivity in agro-climatic regions with higher cost of harvesting area a few areas came out explicitly from the study, where grass root level institutions can play a proactive role in addressing the issue.

Appendix I

Table A1.1: Criteria for classification of RPS

IS Domains	Category A	Category B	Category C	Category D
Infrastructure	Group Processing Centre with Computer and Other Accessories	-	-	-
	Latex Collection Centre	Latex Collection Centre	-	-
	Input Depots with Rubber Procurement	Input Depots	-	-
	Own Office	Office (Rented/Own)	No office	No office
Innovation Capability Building	Agro-management Training	-	-	-
	SHG Formation & SHG Activities	-	-	-
	Capacity Building Programmes – for Tappers and Growers	-	-	-
	Apiculture	-	-	-
Knowledge, Information and Networking	4 General Body Meetings including 1 Annual General Body	2 – 3 General Body Meeting	1 General Body Meeting	No General Body Meetings
	Seminars / Workshops	-	-	-
	8 to 12 Executive	5 – 8 Executive	4 Executive	< 4 Executive
Bridging Institution	Committee Meetings	Committee Meetings	Committee Meetings	Committee Meetings
	Linkage with Rubber Board, Knowledge Infrastructure & RPS Promoted Companies	-	-	-
	Up to Date Audit Report	Audit Report Pending for 1 Year	Audit Report Pending for 2 years	No audit report submitted

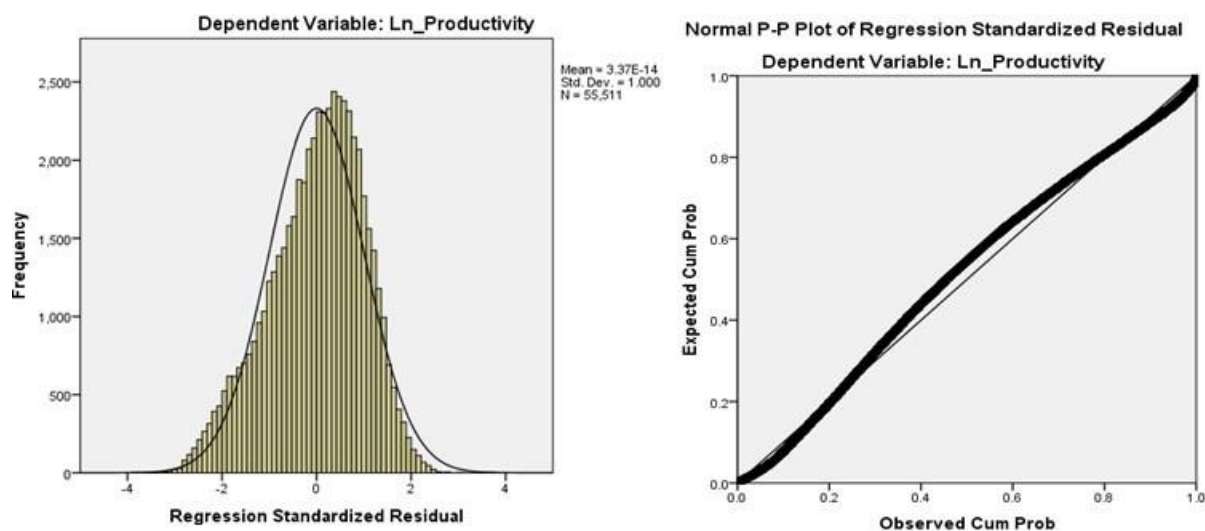
Source: Rubber Board, 2020

Table A1.2: Summary statistics

Variables	Number	Mean	Median	SD	Mini.	Maxi.
Ln _ Productivity	62140	6.71	6.78	0.60	5.20	8.20
Ln _ Untapped Area	65350	5.36	5.38	0.70	2.00	7.69
Ln _ Density of Matured Plants	65225	5.21	5.26	0.29	3.71	7.26
HYV Clone _ Dummy	65149	0.01	0.00	0.12	0.00	1.00
Agro-Dummy _ North South	65534	1.47	1.00	0.50	0.00	1.00
Model RPS _ Dummy	65534	0.09	0.00	0.28	0.00	1.00
IQ Dummy _ Low	58776	0.32	0.00	0.47	0.00	1.00
IQ Dummy _ Medium	58776	0.44	0.00	0.50	0.00	1.00
IQ Dummy _ High	58776	0.24	0.00	0.43	0.00	1.00
Laggards _ Dummy 1	65534	0.17	0.00	0.38	0.00	1.00
Late Majority _ Dummy 2	65534	0.25	0.00	0.43	0.00	1.00
Cost of Harvesting _ Dummy	65534	0.22	0.00	0.42	0.00	1.00

Source: Estimated from Rubber Production Incentive Scheme Data, 2019

Figure A1: Histogram and normal PP Plot of regression standardized residual



Source: Estimated from Rubber Production Incentive Scheme Data, 2019

Table A1.3: Collinearity diagnostics

Independent Variable	VIF
IQ _ Dummy_1	1.190
IQ _ Dummy_3	1.238
Model RPS _ Dummy	1.083
Ln _ Density of Matured Plants	1.260
Agro _ Dummy _ North South	1.907
HYV Clone _ Dummy	1.041
Ln _ Untapped Area	1.245
Cost of Harvesting _ Dummy	1.922
Laggards _ Dummy_1	1.132
Late Majority _ Dummy_2	1.107

Source: Estimated from Rubber Production Incentive Scheme Data, 2019

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Notes

- ¹ Rubber Producer Societies have been initiated as an institutional innovation at the grass root level for collective betterment of smallholders in the natural rubber production sector via better technology transfer, supplies of inputs, capacity building programmes and the so forth in the year 1986 by the Rubber Board and governed by the Charitable Societies Act. The study takes RPS as the institutional arrangement or innovation at the grass root level
- ² The issue of heightened price instability of primary commodity prices in general and agricultural commodity price instability in particular at the global level and the decline in terms of trade vis-a-vis manufactured goods affecting the life of the mass in the developing world is “the commodity problem” quoted here (Maizels, 2003).
- ³ The figures reported for share of agriculture in GVA at basic prices is drawn based on the advanced estimates in the economic survey, 2022-23.
- ⁴ As per the Census Report of 2011 around 25 per cent are cultivators; and 30 per cent are agricultural labourers of the total work force together constituting 55 per cent of the total work force.
- ⁵ The Rubber Board was formed through passing the Rubber Act of 1947. The Coffee Board was set up by an act of parliament in 1942, The Tea Board in 1954 as a result of the parliament act in 1953 and the Cardamom Board in 1964. In 1986 Spices Board was formed by amalgamating Cardamom Board with Spices Export Promotion Council with around 52 major and minor spices under its surveillance.
- ⁶ In the case of Natural Rubber, more than 90 per cent of the growers as of now are smallholders holding less than 5 hectares (Rubber Board, 2020).
- ⁷ The percentage change in price instability index from the pre-reform period to post reform period was found to be the highest in the case of natural rubber as compared to other major plantation crops like Small Cardamom, Black Pepper, Coffee and Tea. While price instability of Natural Rubber increased three times (350 per cent) in the post-reform period as compared to the pre-reform period, price instability declined to the tune of 1.37 per cent and 24.64 per cent for Tea and Small Cardamom respectively and increased to the tune of 73.30 per cent for Black Pepper in the post reform period (Calculated from Price Data of commodities available from Various Commodity Boards).
- ⁸ There are two views of institutions- “institutions as organisations” and “institutions as rules of the game” (Edquist & Johnson, 1997). The study takes the view that institution as organisations with underlying rules of the game governing its activities.
- ⁹ Innovation system approach is disaggregated into different ‘spatially’ and ‘sectorally’ delimited innovation system approaches like national, regional or local (spatial) and sectoral or technological systems (sectorally) based on the object of the study. All these approaches complement each other rather than exclude each other (Johnson et al, 2004)
- ¹⁰ No unanimous definition for co-operation is available in the literature. Generally, it is considered as incompletely specified exchange relationships that leaves room for opportunistic behavior by agents involved in the exchange operations (Fritsch, 2004).
- ¹¹ Though not directly mentioned in Edquist, 1997, in the present study farming households are conceptualized as responders to new knowledge (actors in the ‘innovation process’) developed elsewhere in the system; as farmers need not be a generator of knowledge just like firms in the industrial sector with R & D.
- ¹² Institutions may be traditional tendency towards informal entrepreneurial behavior in the agrarian society like farmers’ exchanges of seeds and planting materials. It may also be more codified laws and regulations governing the behavior of agents.

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- ¹³ A hard institutional failure includes laws, regulations and formalized rules or lack of them preventing innovations and its successful implementation. But there are unwritten local rules, norms, values or culture which may sometimes act as soft institutional failures.
- ¹⁴ By innovation process we mean the creation of an idea or its adoption at the farm level. Hence, innovation is not considered as a single event, rather it is an interactive process involving different stages (Lundvall, 1992).
- ¹⁵ Districts like Kasaragod, Kannur, Kozhikode, Wayanad and Malappuram constitute Northern Zone. North central zone covers Palakkad and Thrissur District. Ernakulam, Idukki and Kottayam falls in the central region and Alappuzha, Kollam, Pathanamthitta and Thiruvananthapuram in the southern region (Veeraputhran et al, 2013)
- ¹⁶ The data has been made available from the Rubber Board
- ¹⁷ Rubber Board's latest recommendation for planting density has been in the range of 420 to 500 plants per hectare. But however, there are significant divergence between the recommended planting density and the actual at the farm level (Veeraputhran et al, 2013)
- ¹⁸ Following this methodology, farmers who are quickly responding to new knowledge / technological developments in the sector (high yielding variety clones in the present study) are treated as innovative farmers (2.5 per cent of the total adopters). The next 13.5 per cent of the farmers who adopted the technology are treated as the early adopters. The early majority (34 per cent) and late majority (34 per cent) are the farmers who adopted the technology in the middle phase of the adoption. The next 16 per cent who came to the technology use in the last phase are the laggards, who are the least experienced in dealing with the technology.
- ¹⁹ As the initial model has been suffering from Heteroskedasticity when White test and Breusch-Pagan test are performed, the study has gone for Heteroskedasticity corrected model with Gretl.
- ²⁰ It could be noted at this juncture that majority of the RPS members in the data were found to be B grade or less than A grade RPS (refer to table 1).
- ²¹ As there are missing observations in some of the variables and some of the villages could not be located from the RPS data base, number of observations in the model varies the actual, which could be inferred from the summary statistics table A1.3 in Appendix I

Innovations for postharvest loss management among smallholder farmers: Evidence from rural Ghana.

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Abstract

In the face of high levels of food losses in agricultural supply chains in developing countries, experts have called for innovations in managing postharvest losses to ensure food and nutrition security. This study employed cross-sectional data from 234 smallholder farmers to assess the usage of postharvest loss innovations in a rural district in Ghana. Descriptive statistics, awareness and perception indices, Path analysis and Kendall's Coefficient of Concordance were employed to analyze the field data. The study revealed the three most patronized innovations for postharvest loss management amongst smallholder maize and cowpea farmers in rural Ghana to include the use of moisture meters, storage in warehouses and the use of mechanical threshers. Awareness about postharvest loss innovations among smallholder farmers was generally low, with radio broadcasts and community information centres being the main sources of information on these innovations in rural communities. However, among farmers who were aware of postharvest loss innovations, perceptions about the technologies were generally positive. The major constraints militating against the uptake and use of postharvest loss innovations were identified to include lack of awareness, limited access to road and storage infrastructure, limited access to agricultural finance and lack of governmental support. A path analysis revealed a significant negative relationship between constraints and level of use of postharvest loss innovations. Perception was found to have a significant conditioning role in reducing the negative effect of constraints on level of use of postharvest loss innovations. Among others, this study recommends the use of radio broadcasts and community information centers to periodically educate and sensitize smallholder farmers to create

awareness and stimulate the adoption of innovative technologies to reduce postharvest losses.

Keywords: Awareness, Innovations, Path analysis, Perception, Postharvest losses.

1.0 Introduction

Agriculture is undoubtedly a major contributor to the Ghanaian economy, employing about 42% of the population and contributing 19% of the country's GDP (Ghana Statistical Service, 2020). It is considered as an essential sector for ensuring food security, poverty reduction and rural development in the country (Anang & Asante, 2020). In terms of export, the sector accounts for approximately 23% of Ghana's total export earnings amounting to \$13.7 billion (Bank of Ghana, 2021). Despite its crucial role in the economy, Ghana's agricultural sector faces significant challenges such as limited access to market, climate change, policy failures, weak institutions and high postharvest losses (Ali et al., 2021). Postharvest losses (PHLs) are a significant challenge affecting the agricultural sector in Ghana, causing food insecurity and economic losses (Sheahan and Barrett, 2017). Kiaya., (2014) defined postharvest losses as the reduction in the quantity and quality of commodities during the period of harvesting and consumption. Maize and cowpea, essential crops supporting the livelihoods of many smallholder farmers, are faced with higher levels of postharvest losses resulting in increased food insecurity issues and economic losses in Ghana.

In rural districts like Ejura-Sekyedumase Municipality of Ghana, where maize and cowpea are central to the food system of households, the impact of PHLs on the welfare of smallholder farmers is glaring as farmers could lose up to 60% and 70% of their maize and cowpea outputs respectively (Obuor et al., 2022). The municipality's economy heavily relies on agriculture, and any significant loss in crop yields has serious implications for both the livelihoods of the farmers and the food security of the municipality. The higher levels of postharvest losses in the area have been attributed to poor harvesting techniques, inadequate storage facilities, and limited access to markets. To mitigate these postharvest losses and improve food security, there is a need to adopt innovative technologies and practices that can reduce PHLs and improve the efficiency of the food supply chain. Several postharvest loss innovations, such as hermetic bags, drying mats, and solar dryers have been developed and introduced to farmers to mitigate food losses. However, postharvest losses are still a major problem in food producing districts in Ghana. Obuor et al, (2022) reported that the persistent high postharvest losses could be attributed to the

limited uptake of postharvest loss innovations amongst farmers and other actors along the agricultural commodity value chains. Damba et al., (2020) also reported that the low uptake and usage of agricultural innovations are mainly due to the numerous challenges associated with their availability, accessibility and efficient implementation. A major gap from the literature on postharvest loss innovations in Ghana however is the limited empirical evidence on the effects of constraints on the uptake and usage of agricultural technologies or innovations. Also, there is limited evidence on the awareness and perception levels as well as the usage of postharvest loss innovations amongst farmers in rural districts and Ghana at large. This study therefore tested the hypothesis that the level of usage of postharvest loss innovations by maize and cowpea farmers in a rural district like Ejura- Sekyedumase municipality is significantly influenced by the constraints they face in using the innovations. Also, the awareness and perception levels of farmers are hypothesized to have a moderating or conditioning effect on the constraints to the usage of the postharvest loss innovations by farmers in rural districts.

This study contributes to the body of literature on postharvest loss innovations by addressing the following questions;

1. What are the awareness levels and perceptions of maize and cowpea farmers on postharvest loss innovations?
2. What is the level of usage of postharvest loss innovations by maize and cowpea farmers in a rural district like in Ghana?
3. What are the constraints militating against the usage of innovative postharvest loss technologies by farmers in rural Ghana? and
4. How do awareness and perception on postharvest loss innovations condition the constraints to achieve usage of PHILs in rural Ghana?

The rest of the paper is segmented into; section 2 which provides a review of relevant studies on postharvest loss innovations, awareness and perceptions levels and constraints analysis whiles Section 3 describes the research methodology adopted for the study. Section 4 presents the results and discussions while the last section presents the conclusions and recommendations for policy.

2.0 Literature review

Postharvest losses in maize and cowpea production can be attributed to several factors, including poor harvesting methods, inadequate storage facilities, insect infestation, and poor processing methods (Kasso & Bekele., 2018; Affognon et al., 2015). According to the Food and Agriculture Organization (FAO, 2021), postharvest losses in developing countries range between 15 and 50% and can lead to devastating effects on food security, nutrition and the general livelihoods of households. Postharvest loss estimates in Ghana are worse than

the regional average as it has been reported to range between 15 and 70% (Gbedemah et al., 2022).

In combating their impact, several Postharvest Loss Innovations (PHLIs) which vary from simple to complex technologies have been developed and introduced to actors in the food supply chain. Postharvest loss innovations are defined as new or improved techniques, technologies, and practices that aim to reduce or prevent the loss of commodities throughout the chain of activities such as storage, transportation, processing, and distribution after harvest (Sugri et al., 2021). Some postharvest loss innovations include improved storage methods (such as hermetic storage bags, metal silos, certified warehouses and grain dryers), improved pest management methods (such as the use of biological control agents), better harvesting, handling and transportation practices as well as processing technologies (Armah, 2019). The effectiveness of these innovations depends on factors such as the crop type, climatic conditions and availability of infrastructure. The advent of these postharvest loss innovations according to Obuor et al., (2022) has yielded some results across the globe. For instance, the introduction of hermetic storage bags and improved drying technologies have led to massive loss reductions in maize and cowpea production. There are a lot of benefits associated with the use of PHLIs to rural households including increased food security, improved nutrition and income to farmers (Bisheko & Rejikumar, 2023). According to Chegere, (2018), the use of PHLIs also results in the use of less costly inputs by farmers leading to cost savings. On the economic front, PHLIs are very significant for nations as they reduce economic stress in the form of reduced food availability, increased prices, lost revenues and high costs of importation (Abraham & Fonta, 2018). According to the FAO, (2021) reducing postharvest losses by just 1% could save enough food to feed millions of people, and increase agricultural incomes by up to \$40 billion annually.

While a range of postharvest loss innovations have been developed to address the menace of postharvest losses, the effectiveness of these innovations has been limited in many instances due to the limited level of awareness and knowledge among farmers. Some studies have revealed the limited level of awareness of PHLIs in many developing countries, including Ghana. Obuor et al., (2022) reported that the majority of cereal farmers in Ghana were not aware of postharvest loss innovations, and even amongst those that were aware, there was limited knowledge on how to use them effectively. Abass et al., (2014) also reported that farmers in Tanzania had limited knowledge of postharvest loss innovations, which was a significant barrier to their adoption and usage. The major factors contributing to the low awareness levels of PHLIs amongst farmers in the sub-region are; lack of access to information, inadequate dissemination channels and poor communication strategies, inadequate financial resources and limited access to extension services (Mohammed, 2018).

Recently, there have been the implementation of some initiatives to improve the awareness levels of PHLIs amongst farmers. For instance, the USAID Feed the Future initiative in Ghana has been promoting the adoption of improved postharvest handling and storage technologies, such as hermetic bags and moisture meter, through training programs and extension services (Gbedemah et al., 2022). Also, the African Development Bank (ADB) launched the Technologies for African Agricultural Transformation (TAAT) program with the aim of promoting the adoption of postharvest loss innovations in several African countries, including Ghana (Bisheko & Rejikumar, 2023). Despite these initiatives, there are still records of high postharvest losses amongst maize and cowpea farmers in Ghana.

The perception of farmers towards PHLIs is very crucial for its adoption and usage. Sugri et al., (2021) reported that farmers who perceived hermetic bags as effective in reducing their level of losses were more likely to adopt them. Also, Abass et al. (2014) reported that farmers who perceived the benefits associated with the use of PHL innovations, such as improved crop quality, increased market opportunities and increased shelf life of commodities, were more likely to adopt them. Perception of farmers towards these PHLIs are however influenced by several factors including socio-economic characteristics, cultural beliefs, access to information, availability of resources and past experiences (Amponsah et al., 2021; Elemasho et al., 2017). Farmers' perception of PHL innovations is however not always based on rational decision-making but can also be influenced by social and psychological factors such as their perceived social status, the need to conform to social norms and expectations as well as by their level of trust in extension agents and other sources of information (Afodu et al., 2020; Tesfaye & Tirivayi 2018).

Some studies have shown that the level of usage of PHLIs amongst farmers is generally low (Swai et al., 2019; Alhassan and Kumah, 2018; Opit et al., 2014). This has been attributed to a lot of factors such as awareness and perception of farmers, financial resources, social networks and limited access to extension services (Kwarteng Amaning et al., 2019). Abdoulaye et al., (2018) stated that farmers with access to financial resources are more likely to invest in PHLIs for their production activities. Obiero et al., (2019) also reported that the level of education and access to trainings on the use of PHLIs of farmers play a critical role in their usage by farmers.

Despite the benefits associated with the adoption and use of PHL innovations, farmers experience several challenges in adopting and implementing these innovations (Sonka & Shah, 2023). Apart from the low levels of awareness and perception of farmers on the PHL innovations, some of the challenges to the usage of PHL innovations are; high cost of PHL innovations, cultural and traditional beliefs and inadequate infrastructure (Sugri et al., 2021). The high

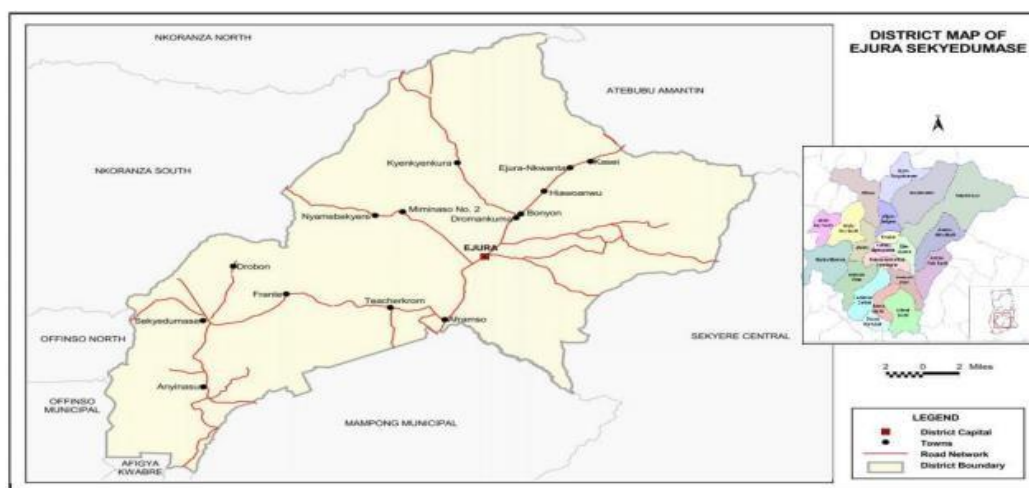
cost of PHL innovations hinder a lot of farmers, especially smallholder farmers who have limited financial resources from adopting them for their production activities (Danso-Abbeam et al., 2018). It is reported that some farmers view traditional methods of storage and preservation to be more effective and reliable than modern innovations (Sugri et al., 2021).

3.0 Methodology

3.1 Data

This study was carried out in one of Ghana's rural districts (Ejura-Sekyedumase municipality) in the Ashanti region of the country (Figure 1). The district covers an area of approximately 1,238 km² with a population of about 85,000 people (GSS, 2022). It is situated between the coordinates 7.3833° N and 1.3667° W. It is characterized by two main cropping seasons; wet/ major season spanning from April to October and the dry/ minor season between November and March. The municipality is predominantly rural, with agriculture being the main economic activity of the indigenes. Maize and cowpea are the major crops cultivated by farmers in the municipality, grown for both subsistence and commercial purposes (Wognaa et al., 2019). Despite the significant contribution of maize and cowpea to the local economy, the municipality experiences high postharvest losses, which according to Obuor et al., (2022) can be attributed to poor postharvest handling practices, inadequate storage facilities, and limited access to postharvest innovations.

Figure 1.0: Map of Ejura-Sekyedumase Municipality



Source: GSS, 2013.

Farmers who cultivated maize and cowpea in the 2021 cropping season were considered for the study. Data collection was achieved by employing

quantitative research techniques in gathering cross-sectional data from the farmers between August and September 2022. A four-stage sampling procedure was followed in sampling farmers for the study. In the first stage, the Ejura-Sekyedumase municipality was purposively selected due to the high volumes of maize and cowpea produced in the area and the associated high postharvest losses (Opit et al., 2014). In the second stage, two major maize and cowpea producing communities (Kasei & Anyinasu for maize and Hiawoanwu & Miminaso No. 1 for cowpea) were selected in consultation with Agricultural Extension Agents (AEAs) in the municipality. A total sample size of 246 was determined by the adoption of the Yamane formula for sample size determination (equation 1). Proportional sampling was then used in the third stage to determine farmers to be selected from each of the chosen communities as shown in Table 1. With the help of the randomization command in Microsoft excel, maize and cowpea farmers were selected in the fourth stage using the farmers' list.

$$n = \frac{N}{1+N(\alpha^2)} \quad [1]$$

Where: n represents the expected sample size, N is the total population for the study and α is the margin of error (0.05).

Out of the 246 targeted respondents for the study, total valid responses from 126 maize farmers and 108 cowpea farmers, representing a response rate of 94.7% were used for analysis.

Table 1: Communities, their population and samples drawn for the study

Communities	Population	Sample
Kasei	104	69
Anyinasu	93	63
Hiawoanwu	82	59
Miminaso No 1	77	55
Total	356	246

Table 2 illustrates the socio-economic characteristics of maize and cowpea farmers and summary statistics of the pooled sample. Out of the 234 responses from farmers, male representation was 53% while that of females was 47%. Even though it obviously reveals that males were dominant in maize and cowpea farming, it however shows an improvement in female involvement in

maize and cowpea production in the area. This confirms the findings of Dittoh et al., (2015) who reported that with the priority treatment given to females in agricultural production activities by the Women in Agriculture Development (WIAD) department of the Ministry of Food and Agriculture (MoFA), female involvement in agricultural production activities is expected to increase. While adults older than 50 years represented 26.1% of the respondents, percentage of farmers within the ages of 25 and 50 years was 73.9% depicting an improvement of the involvement of the youth in agricultural activities in the municipality. As high as 59% of the farmers have had some level of formal education with 41% not having any formal education at all. This also confirms the finding of Anang et al., (2020) who reported that agriculture is no longer the occupation of the illiterates but have experienced massive investments from people with varying levels of education. Table 2 also reveals that as high as 84.6% of farmers in the municipality were operating their farms under the rent land tenure system while only 6.8% have outrightly purchased the lands for their production activities. Sixty-three (63.2) percent of the farmers reported to sell their produce outside the community market while only about twenty (19.7) percent sold their commodities at the farm gate. This result is consistent with the assertion of Adams et al., (2022) that, sale of commodities at farm gate was reported amongst farmers to amount to a huge economic loss to them since the price quotes of aggregators and wholesalers were unreasonably low. Forty-one (41) percent of the farmers had received some form of trainings on postharvest loss innovations while as high as 59% had not received any trainings. On receiving information relevant for their production activities, 35.9%, 10.7 and 27.8 percents of respondent reported to have gotten them from radio, television and information centres respectively. While 16.2% get production information from extension agents, 9.4% received it from others sources such as their neighbours and colleague farmers etc. This result confirms the study of Attuh & Kankam, (2022) that the basic means of disseminating agricultural information to rural household are through the radio and television. Obeng-Fosu, (2021) also reported that there is a new and emerging means of information dissemination through the community information centres where mass announcements are made.

3.2 Theoretical framework

The level of usage of postharvest loss innovations in this study is hypothesized to be influenced by the awareness and perception levels of farmers as well as the challenges they are exposed to. There are several theories that have been developed to capture the adoption and level of usage of innovations. For instance, the Technology Acceptance Model (TAM) proposes that perceived usefulness and perceived ease of use of an innovation are key factors considered before the uptake of innovations (Ambong & Paulino, 2020). It is widely used due to its ability to be readily understood and the provision of a

framework that takes into account various factors that influence innovation acceptance and adoption (Al-Qaysi et al., 2021). It is however limited in scope as it mainly focuses on individual-level factors influencing innovation adoption without considering the influence of environmental and other social factors that may influence innovation adoption and usage (Shachak et al., 2019). These shortcomings are addressed by the Diffusion of innovation theory which considers all other external factors influencing the adoption and usage of an innovation as well as having the capacity to be used by policy makers and developers in designing and implementing interventions (Djoumessi, 2021). The Diffusion innovation theory therefore identifies several factors that influence the rate of adoption of an innovation including the perceived relative advantage, compatibility and observability of the innovation. The Theory of Planned Behaviour (TPB) is another theory developed to complement the diffusion of innovation theory with the aim of explaining how people's attitudes, subjective norms and perceived behavioural controls influence their intentions and actual behaviours (Kamrath et al., 2018). TPB is therefore a social psychological theory that suggest that adoption and usage of innovations is based on the overall perception of a person regarding the innovation. de Sena Abrahão et al., (2016) however suggested that, the adoption of Structural Equation Modelling (SEM) approach as an analytical tool for examining the relationships between constructs influencing the adoption and usage of innovations, the Unified Theory of Acceptance and Use of Technology (UTAUT) is the suitable theory to use. This is because, it integrates all the three theories (Technology Acceptance Model (TAM), the Theory of Planned Behaviour (TPB), the Innovation Diffusion Theory (IDT)) discussed above as a composite theory. By incorporating the key concepts from these multiple theories, it offers a more complete picture of the complex factors that influence innovation adoption and usage.

The UTAUT posits that four key factors shape an individual's intention to adopt and use new innovations namely; performance expectancy (the degree to which the technology is perceived as useful and easy to use), effort expectancy (the degree to which using the technology is perceived as easy), social influence (the degree to which social norms and pressure shape the use of the technology), and facilitating conditions (the degree to which the necessary resources and support are available to use the technology) (Kamrath et al., 2018). With the advantages of being comprehensive in nature, having a high predictive ability and more flexible to use, the Unified Theory of Acceptance and Use of Technology is therefore the theory underpinning this study.

Table 2: Demographic characteristics of farmers

Variable	Categories	Maize (n=126)		Cowpea(n=108)		Pooled sample(N=246)	
		Frequency	Percent	Frequency	Percent	Frequency	Percent
Sex	Male	64	50.8	60	55.6	124	53.0
	Female	62	49.2	48	44.4	110	47.0
Age	<25 years	46	36.5	39	36.1	85	36.3
	25-50 years	54	42.9	34	31.5	88	37.6
	>50 years	26	20.6	35	32.4	61	26.1
Education	No formal education	51	40.5	45	41.7	96	41.0
	Basic	47	37.3	36	33.3	83	35.5
	Secondary	20	15.9	22	20.4	42	17.9
	Tertiary	8	6.3	5	4.6	13	5.6
Marital status	Single	45	35.7	39	36.1	84	35.9
	Married	55	43.7	53	49.1	108	46.2
	Divorced	17	13.5	9	8.3	26	11.1
	Widowed	9	7.1	7	6.5	16	6.8
Land tenure	Purchased	9	7.1	7	6.5	16	6.8
	Leased	11	8.8	9	8.3	20	8.5
	Rented	106	84.1	92	85.2	198	84.6
	Both	90	71.4	95	88.0	185	79.1
Main sales point	Farm gate	26	20.6	20	18.5	46	19.7
	Market within community	26	20.6	14	13.0	40	17.1
	Market outside community	74	58.8	74	68.5	148	63.2
Access to credit	Yes	27	21.4	26	24.1	53	22.6
	No	99	78.6	82	75.9	181	77.4
Membership to FBO	Yes	82	65.1	64	59.3	146	62.4
	No	44	34.9	44	40.7	88	37.6
Trainings on PHL innovations	Yes	59	46.8	37	34.3	96	41.0
	No	67	53.2	71	65.7	138	59.0
Sources on information	Radio	40	31.7	44	40.7	84	35.9
	Television	15	11.9	10	9.3	25	10.7
	Information centre	32	25.4	33	30.6	65	27.8
	Extension agents	19	15.1	19	17.6	38	16.2
	Colleague farmers	20	15.9	2	1.9	22	9.4

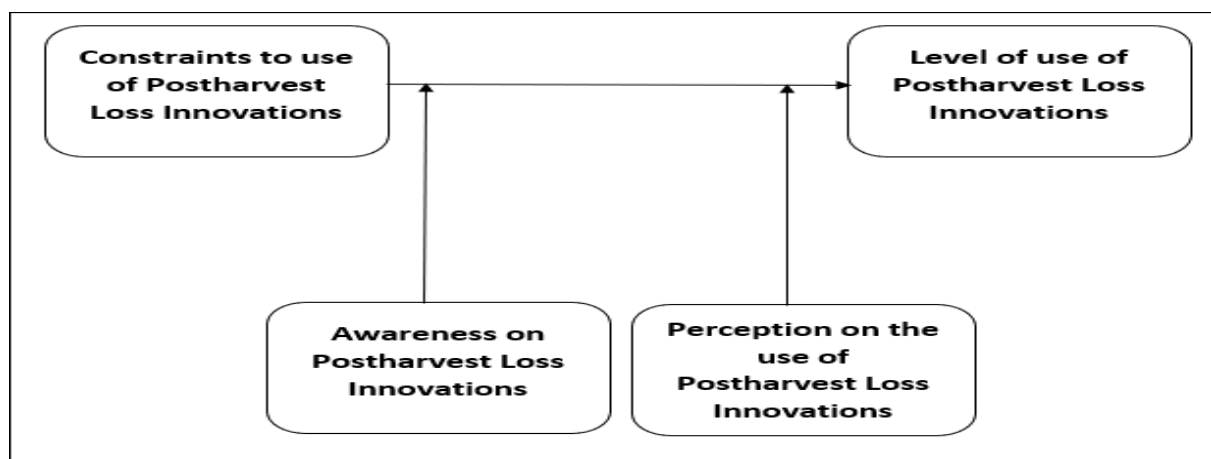
3.3 Conceptual framework

The level of usage of postharvest loss innovations by maize and cowpea farmers in the Ejura- Sekyedumase municipal is hypothesized to be influenced by the constraints they face in the use of the innovations. The study however hypothesizes that awareness and perception levels of farmers on postharvest loss innovations can have a moderating or conditioning effect on the constraints to the usage of PHLIs and enhance usage levels of PHLIs by farmers. The awareness level brings to light the degree to which farmers are knowledgeable about the postharvest loss innovations at their disposal, the potential benefits they stand to gain as well as the level of communication between farmers and other stakeholders in the sector. The perception levels of farmers on the other hand reveals the attitudes of farmers towards postharvest loss innovations such as their perceived usefulness, ease of use and compatibility with existing farming practices in the locality. The challenges faced by farmers refers to the barriers and constraints they face in adopting and using the postharvest loss innovations available to them. These include factors such as; lack of necessary knowledge or skills to effectively implement PHLIs, lack of trainings on the use of PHLIs and limited premium for high-quality postharvest loss-reduced crops amongst others. In testing the hypotheses that these factors influence the level of usage of postharvest loss innovations in the municipality, Path Analysis was

performed using Haye's process macro plugin in SPSS, this was done to examine the conditioning effects of awareness levels and perception levels, on the relationship between the constraints faced by farmers and the level of usage of postharvest loss innovations in the locality. Figure 2 illustrates the conceptual framework for this study. The following hypotheses are proposed from the conceptual model;

- H1:** Constraints negatively influence the level of usage of PHLIs.
- H2:** Awareness positively conditions the relationship between constraints and level of use of PHLIs such that the negative relationship between constraints and level of use is inhibited.
- H3:** Perception positively conditions the relationship between constraints and level of use of PHLIs such that the negative relationship between constraints and level of use is inhibited.

Figure 2. Conceptual framework



Source: Authors' construct

3.4 Analytical framework

Awareness and perception indices

Farmers' perception of postharvest loss innovations and how it influences their usage was assessed using a five-point likert scale namely; strongly disagree (1), disagree (2), neutral (3), agree (5), and strongly agree (5). Perception is defined as the interpretation and understanding of sensory information by an individual, which is influenced by their experiences, expectations, and attitudes (Puspitasari et al., 2017). In this study, farmers' perception of postharvest loss innovations is considered as how farmers perceive the usefulness, feasibility, and relevance of these innovations in reducing their postharvest losses.

Perception statements on the postharvest loss innovations were presented to the farmers and their levels of agreement captured using the 5-point likert scale. Perception statements categorized under two main themes (availability and accessibility of postharvest loss innovations and perception on the benefits of using postharvest loss innovations) were presented to farmers to choose the best option pertaining to their case. The mean score (MS) of the perception statements under the two themes are computed to arrive at the overall Perception Index (PI). The mean scores (MS) of the perception statements are arrived at by using this formula;

$$MS_p = \frac{[(fsd \times 1) + (fd \times 2) + (fn \times 3) + (fa \times 4) + (fsa \times 5)]}{x} \quad [2]$$

where MSP represents mean score of perception, fsd represents frequency of strongly disagree, fd represents frequency of disagree, fn represents frequency of neutral, fa represents frequency of agree, fsa represents frequency of strongly agree and x = total number of responses to the perception statement.

The perception index (PI) is computed by using;

$$PI = \frac{[MS_{availability} + MS_{benefits}]}{n} \quad [3]$$

where $MS_{availability}$ = perception on the availability and accessibility of postharvest loss innovations and $MS_{benefits}$ = perception of farmers on the benefits of using postharvest loss innovations and n represents the number of mean scores (2 in this case).

Farmers knowledge and awareness of postharvest loss innovations was also assessed under two main themes (knowledge of the awareness of the use of postharvest loss innovations and awareness of the use of postharvest loss innovations). The five-point likert scale specified about is also adopted for assessing the awareness index. Following the computations of the mean scores (MS) and Perception index (PI) in equations [1] and [2] above, the mean scores and the awareness index (AI) are computed as follows;

$$MS_A = \frac{[(fsd \times 1) + (fd \times 2) + (fn \times 3) + (fa \times 4) + (fsa \times 5)]}{x} \quad [4]$$

$$AI = \frac{[MS_{Knowledge} + MS_{benefits}]}{n} \quad [5]$$

Where MSA represents the Mean score of awareness, $MS_{Knowledge}$ represents awareness of the knowledge on the use of postharvest loss innovations and

MSbenefits represents awareness of the benefits of using postharvest loss innovations.

Path analysis

The study used SmartPLS to perform a confirmatory factor analysis of the various constructs under study. In performing the confirmatory factor analysis, reliability of the items was assessed by using Cronbach alpha and composite reliability. The reliability of measurement items refers to the consistency and stability of the responses obtained from the measurement instrument over time and across different groups of individuals (Peterson & Kim, 2013). Furthermore, the convergent validity of the items was assessed by using the Average Variance Extracted. Convergent validity is a type of validity that assesses the degree to which different measurement instruments that are supposed to measure the same construct are correlated. In other words, convergent validity is the extent to which two or more measures that are designed to assess the same construct yield similar results (Cheung et al., 2023). The Fornell-Lacker criterion and cross-loadings was used to assess the discriminant validity of the items. Discriminant validity is a type of validity that assesses the degree to which two different measurement instruments that are supposed to measure different constructs are not correlated. In other words, discriminant validity is the extent to which two or more measures that are designed to assess different constructs yield different results (Hamid et al., 2017). Further, path analysis was performed by using Haye's Process Macro plugin in SPSS. The process macro uses ordinary least squares regression to calculate various models to test for mediation, moderation, and conditional indirect effects. (Hayes, 2013).

Constraints analysis using kendall's coefficient of concordance

The Kendall's coefficient of concordance (W) is a non-parametric measure of agreement or concordance among multiple raters or judges for ordinal or ranked data (Alcaraz et al., 2022). It measures the degree to which the raters agree on the relative ordering of a set of items or variables. It is also known as Kendall's coefficient of rank correlation. It is computed by comparing the observed concordance among the raters' rankings to the expected concordance under the null hypothesis of no agreement. The expected concordance is based on the assumption that the raters are independent and that each item is equally likely to be ranked first, second, third, and so on. It is therefore used to assess the reliability or consistency of measurements made by multiple raters or judges, such as in the case of inter-rater or inter-judge reliability. Kendall's W ranges from 0 to 1, where 0 indicates no agreement among the raters beyond what would be expected by chance, and 1 indicates perfect agreement among the raters. Generally, Kendall's W above 0.7 are considered to indicate higher levels of agreement among the raters while values below 0.4 indicate lower

levels of agreement (Newman & Sin, 2020). Taking into consideration the challenges affecting the usage of postharvest loss innovations by farmers in the Ejura-Sekyedumase, the Kendall's coefficient of concordance is helpful in assessing the level of agreement or degree of similarity among the rankings given by the different farmers on a set of constraints they face in relation to their postharvest activities. The formula for Kendall's W involves the sum of squared deviations of each item's rank from the mean rank across all raters, multiplied by a weighting factor that depends on the number of raters and the number of items. Following Mensah et al., (2017), the Kendall's coefficient of concordance is specified as;

$$W = \frac{12S}{p^2(n^3 - n) - pT} \quad [5]$$

where; S is the sum of squares from row sum of rank numbers, n is number of objects, P is number of judges and T is the correction factor for ties in ranks.

4.0 Results and discussion

4.1 Awareness of farmers on the use of postharvest loss innovations

Table 3 illustrates the results on the awareness of maize and cowpea farmers on postharvest loss innovations for their production activities in the Ejura-Sekyedumase municipal of Ghana. Using a 5-point likert scale ranging from 1 to 5 where 1 is strongly disagree and 5 is strongly agree, the results indicated that the awareness index of farmers of the knowledge on the use of postharvest loss innovations was 3.7. This suggests that maize and cowpea farmers generally agreed to the awareness statements captured under the knowledge thematic area. For instance; about seventy- one (70.5) strongly agreed to the awareness statement that “many postharvest loss innovations exist that can help reduce losses and improve crop quality”. This result is consistent with the findings of Affognon et al., (2015) who reported that even though there is a lot of information dissemination to be done on postharvest loss innovations, most farmers are aware of the availability of these innovations within the sector. Awareness of 3.0 under the benefits of using postharvest loss innovations thematic area however indicates that farmers were indifferent on the benefits associated with the adoption and use of the postharvest loss innovations available to them. For instance, about fifty-one percent of the farmers jointly indicated their disagreement to the statement “proper postharvest handling can help ensure the safety and quality of our crops, making them more attractive to buyers and consumers”. This result suggests that even though farmers are aware of the availability of the existence of postharvest loss innovations, their level of awareness on the benefits of its usage is very minimal; a barrier that can impede

the uptake of these innovations in the municipality.

4.2 Perception of farmers on the use of postharvest loss innovations

Perceptions of farmers on the postharvest loss innovations are presented in Table 4. The study revealed that maize and cowpea farmers in Ejura-Sekyedumase generally have a positive perception about postharvest loss innovations. An overall perception index of 4.4 suggests that farmers generally agreed to the perception statements presented to them. This is consistent with the study of Obuor et al., (2022) who recorded that farmers usually have a positive perception about technologies and innovations aimed at improving their production activities and overall livelihoods. In assessing their perception under the availability and accessibility of postharvest loss innovations, about fifty-two (51.7) percent of the farmers reported there are some innovations available to them in the municipality to reduce their postharvest losses. Sixty-three (63.3) percent of them however perceive that these innovations will bring much satisfaction to them if more education and training to understand their use and implementation is carried out in the municipality. Danso-Abbeam et al., (2018) reported in their study that dissemination of extension information amongst farmers is one of the major challenges in the Ghanaian agricultural sector due to the high extension farmer-to-farmer ratio. Farmers perceived that the uptake of postharvest loss innovations will be beneficial to their production activities as it helped save money by reducing the quantity of crop losses (92.3%), storing of commodities over a longer period (71.8%) and help in the reduction of environmental waste and pollution (89.3%).

4.3 Level of usage of postharvest loss innovations

Table 5 presents a list of the postharvest loss innovations identified in a reconnaissance survey to be adopted by maize and cowpea farmers in the Ejura-Sekyedumase. A five-point Likert scale where 1 indicates the decision of never using the innovation and 5 represents always using the innovation was adopted in assessing the level of use of the postharvest loss innovations. The results indicated that most farmers were using these innovations in their production activities with the use of moisture meters, warehouses and mechanical threshers recording higher levels of usage of 55%, 50.9% and 49.6% respectively. With the exception of the use of chemical treatments, actively patronized the usage of all the other innovations in excess of 30%. The high level of usage of these innovations can be attributed to the high and positive perceptions of farmers of postharvest loss innovations in the study area. These findings are consistent with the report of Simpson, (2015) who stated that positive perceptions about agricultural innovations is a precursor for their adoption and usage. Adopting the Kendall's coefficient of concordance in assessing the rankings of the postharvest innovations adopted by farmers

showed that, the three most used innovations by maize and cowpea farmers in the study were the use of moisture meters, storage of commodities in warehouses and the use of mechanical threshers. The Kendall's W of 12.7% depicts a low level of agreement amongst the farmers in the innovations they use in their activities.

4.4 constraints militating against the usage of postharvest loss innovations

Tables 7 and 8 present the result on the challenges to the usage of PHLIs in the Ejura-Sekyedumase municipal of Ghana analysed using a five-point likert scale and Kendall's Coefficient of concordance. As illustrated in Table 7, 89.3%, 85.9% and 77.4% generally agreed to the challenges of lack of adequate infrastructure (e.g., storage, road networks), limited access to financing to and limited government and policy support. Table 8 also confirms that the first three constraints militating against the use of postharvest loss innovations are the lack of adequate infrastructure (eg. storage, road networks), limited access to financing to and limited government and policy support. In Ejura-Sekyedumase for instance, majority of the farms where these commodities are cultivated are far from motorable roads making it difficult for easy transportation and carting to market centres; which worsens the postharvest losses. These results confirm a MoFA, (2018) report that the challenges associated with postharvest systems in Ghana are a continuum between poor sectoral policy formulations and inadequate infrastructure for production activities. Kumar & Kalita, (2017) also reported that until recently, there was no policy directive on the postharvest loss reduction in the agricultural sector in Ghana, a phenomenon that has resulted in minimal successes in postharvest loss mitigation activities in Ghana. Other constraints to the usage of postharvest loss innovations are limited market demand and market access, limited premium for high-quality, postharvest loss-reduced crops as well as limited trainings and education on the use of postharvest loss innovations. The Kendall's W of 0.24 suggests that there is twenty-four percent agreement between the farmers on the rankings given to the constraints limiting their usage of postharvest loss innovations.

Table 3: Awareness of farmers about postharvest loss innovations

Awareness Statements	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Awareness Index
<i>Awareness of the knowledge on the use of postharvest loss innovations</i>						
Many postharvest loss innovations exist that can help reduce losses and improve crop quality	5 (2.1)	5 (2.1)	24 (10.3)	34 (14.5)	166 (70.9)	4.5
It's important for us as farmers to stay informed and up-to-date on the latest postharvest loss technologies and techniques.	18 (7.69)	17 (7.26)	59 (25.21)	51 (21.79)	89 (38.03)	3.8
Postharvest loss innovations can help us store crops for longer periods, giving us more flexibility in when and where we sell them."	16 (6.8)	21 (9.0)	53 (22.7)	57 (24.4)	87 (37.2)	3.8
Proper postharvest handling is crucial to reducing losses and ensuring the safety and quality of our crops	22 (9)	27 (12)	47 (20)	52 (22)	86 (37)	3.7
Postharvest loss innovations can also help reduce our environmental impact by reducing waste and increasing efficiency	101 (43.2)	50 (21.4)	34 (14.5)	26 (11.1)	23 (9.8)	2.2
There are many training and educational resources available to help us learn about and implement postharvest loss technologies	16 (6.8)	12 (5.1)	30 (12.8)	53 (22.7)	123 (52.6)	4.1
<i>Mean score of Awareness of Knowledge on the use of PHLIs (MS Knowledge)</i>						3.7
<i>Awareness of the benefits of using postharvest loss innovations</i>						
Postharvest loss innovations can help us store crops for longer periods, giving us more flexibility in when and where we sell them	8 (3.4)	23 (9.8)	62 (26.5)	42 (18.0)	99 (42.3)	3.9
Proper postharvest handling can help ensure the safety and quality of our crops, making them more attractive to buyers and consumers	76 (32.5)	43 (18.4)	37 (15.8)	41 (17.5)	37 (15.8)	2.7
Using postharvest loss innovations can help reduce losses and increase our income by allowing us to sell more high-quality crops	60 (26)	27 (12)	56 (24)	40 (17)	51 (22)	3.0
By using postharvest loss technologies, we can provide safer and better-quality food for our families and communities	66 (28.2)	43 (18.4)	43 (18.4)	31 (13.3)	51 (21.8)	2.8
Postharvest loss innovations can also help reduce postharvest labour, allowing us to save time and focus on other aspects of our farms	150 (64.1)	31 (13.3)	27 (11.5)	15 (6.4)	11 (4.7)	1.7
By using postharvest loss technologies, we can contribute to the global effort to reduce food waste and ensure food security for all	29 (12.4)	24 (10.3)	44 (18.8)	53 (22.7)	84 (35.9)	3.6
<i>Mean score of Awareness of Benefits of using PHLIs (MS Benefits)</i>						3.0
<i>Overall Awareness Index</i>						3.4

Figures in parenthesis are in percentages

Table 4: Perception on Postharvest loss innovations.

Perception Statements	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Perception Index
<i>Availability and accessibility of postharvest loss innovations</i>						
I have heard about some postharvest loss innovations, but I don't know much about them and how they work	2 (0.9)	1 (0.4)	31 (13.3)	69 (29.6)	130 (55.8)	4.4
I think there are some innovations available to reduce postharvest losses, but they may not be easily accessible to small-scale farmers like me	2 (0.9)	2 (0.9)	27 (11.5)	82 (35.0)	121 (51.7)	4.4
I think that postharvest loss technologies should be tailored to meet the needs of small-scale farmers and their specific crops	1 (0.4)	1 (0.4)	32 (13.7)	77 (32.9)	123 (52.6)	4.4
I believe that the cost of some postharvest loss technologies is too high for small-scale farmers to afford	2 (0.9)	4 (1.7)	24 (10.3)	86 (36.8)	118 (50.4)	4.3
I believe that postharvest loss innovations could greatly benefit our farming community, but we need more education and training to understand and implement them	1 (0.4)	6 (2.6)	14 (6.0)	65 (27.8)	148 (63.3)	4.5
I have seen some farmers successfully implement postharvest loss innovations, but it requires a lot of effort and resources.	0 (0.0)	1 (0.4)	21 (9.0)	67 (28.6)	145 (62.0)	4.5
I think it's important for farmers to work together to share knowledge and resources on postharvest loss innovations	0 (0.0)	5 (2.1)	24 (10.3)	90 (38.5)	115 (49.2)	4.3
<i>Mean score of perception on the availability and accessibility of PHLIs (MS Availability)</i>						4.4
<i>Perception on benefits of using postharvest loss innovations</i>						
Using postharvest loss innovations has helped me save money by reducing the quantity of crops lost after harvest	1 (0.4)	1 (0.4)	16 (6.8)	82 (35.0)	134 (57.3)	4.5
I have noticed that my income has increased since implementing postharvest loss innovations, as I am able to sell more high-quality crops	5 (2.1)	1 (0.4)	19 (8.1)	74 (31.6)	135 (57.7)	4.4
Postharvest loss innovations have enabled me to store my crops for longer periods, giving me more flexibility in when and where I sell them	9 (3.9)	17 (7.3)	40 (17.1)	82 (35.0)	86 (36.8)	3.9
I feel more confident in investing in my farm knowing that I have postharvest loss technologies to reduce losses and improve profitability	3 (1.3)	2 (0.9)	19 (8.1)	75 (32.1)	135 (57.7)	4.4
Postharvest loss innovations have also helped me reduce my environmental impact by reducing waste and increasing efficiency	2 (0.9)	5 (2.1)	18 (7.7)	73 (31.2)	136 (58.1)	4.4
I feel proud to be a farmer who is using modern technologies and techniques to improve my farm and community	3 (1.3)	8 (3.4)	34 (14.5)	93 (39.7)	96 (41.0)	4.2
<i>Mean score of perception on the benefits of using PHLIs (MS Benefits)</i>						4.3
<i>Overall Perception Index</i>						4.4

Figures in parenthesis are in percentages

Table 5: Level of use of postharvest loss innovations

Postharvest loss innovations	Never	Rarely	Sometimes	Often	Always
Use of insect-resistant varieties	.3)	7 (3.0)	51 (21.8)	92 (39.3)	81 (34.6)
Use of threshing equipment	1 (0.4)	5 (2.1)	27 (11.5)	85 (36.3)	116 (49.6)
Use of hermetic storage	3 (1.3)	4 (1.7)	41 (17.5)	98 (41.9)	88 (37.6)
Use of organic pesticides	2 (0.9)	9 (3.9)	36 (15.4)	91 (38.9)	96 (41.0)
Use of drying sheets	2 (0.9)	5 (2.1)	53 (22.7)	90 (38.5)	84 (35.9)
Use of chemical treatments	6 (2.6)	35 (15.0)	63 (26.9)	75 (32.1)	55 (23.5)
Use of proper transportation	6 (2.6)	15 (6.4)	61 (26.1)	80 (34.2)	72 (30.8)
Use of moisture meters	2 (0.9)	3 (1.3)	24 (10.3)	76 (32.5)	129 (55.1)
Use of storage rooms/warehouses	3 (1.3)	7 (3.0)	20 (8.6)	85 (36.3)	119 (50.9)
Use of air-tight containers	1 (0.4)	3 (1.3)	29 (12.4)	102 (43.6)	99 (42.3)

Figures in parenthesis are in percentages

Table 6: Kendall's ranking of postharvest loss innovations

Postharvest loss innovations	Mean score	Rank
Use of moisture meters	6.53	1st
Use of storage rooms/warehouses	6.27	2nd
Use of threshing equipment	6.27	3rd
Use of airtight containers	5.97	4th
Use of organic pesticides	5.64	5th
Use of hermetic storage	5.52	6th
Use of drying sheets	5.25	7th
Use of insect-resistant varieties	5.18	8th
Use of proper transportation	4.60	9th
Use of chemical treatments	3.76	10th
Kendall's W		0.127
Chi-square		267.764
df		9
Asymptotic significance		0.00

Table 7: Challenges affecting the usage of postharvest loss innovations

Challenges	SA	A	N	D	SD
Lack of awareness and understanding of the use of PHLIs	25 (10.7)	42 (18.0)	67 (28.6)	69 (29.5)	31 (13.3)
Lack of training and education on the use of PHLIs	12 (5.1)	25 (10.7)	61 (26.1)	72 (30.8)	64 (27.4)
Lack of necessary knowledge or skills to effectively implement PHLIs	20 (8.6)	34 (14.5)	63 (26.9)	68 (29.1)	49 (20.9)
Lack of adequate infrastructure (eg. Storage and transportation infrastructure)	2 (0.9)	0 (0.0)	23 (9.8)	102 (43.6)	107 (45.7)
Limited access to financing/ source of capital	2 (0.9)	4 (1.7)	27 (11.5)	91 (38.9)	110 (47.0)
Limited market demand and market access	6 (2.6)	16 (6.8)	63 (26.9)	99 (42.3)	50 (21.4)
Limited premium for high-quality, postharvest loss-reduced crops	9 (3.9)	16 (6.8)	66 (28.2)	94 (40.2)	49 (20.9)
Limited government and policy support	3 (1.3)	10 (4.3)	40 (17.1)	76 (32.5)	105 (44.9)

Figures in parenthesis are proportions of respondents

Table 8: Ranking of challenges affecting the usage of PHLIs

Challenges	Mean score	Rank
Lack of adequate infrastructure (e.g., Storage and transportation infrastructure)	5.81	1st
Limited access to financing/ source of capital	5.69	2nd
Limited government/ policy support	5.40	3rd
Limited market demand and market access	4.22	4th
No price incentives (premium price) for high-quality produce	4.15	5th
Lack of training and education on the use of PHLIs	4.07	6th
Limited knowledge/ skills to effectively implement PHLIs	3.56	7th
Lack of awareness and understanding of the use of PHLIs	3.10	8th
<i>Kendall's W^a</i>		0.240
<i>Chi-Square</i>		392.550
<i>df</i>		7
<i>Asymp. Sig.</i>		0.000

4.5 The conditioning effects of awareness and perception of PHLIs on constraints to the usage of PHLIs

4.5.1 Confirmatory factor analysis

To assess the conditioning effects of awareness and perception of PHLIs on the relationship between constraints and usage of PHLIs, a confirmatory factor analysis was first performed using SmartPLS to ensure the validity and

reliability of the measures. 12, 13, 10 and 8 measures were developed based on extensive literature review and expert interviews to measure awareness, perception, level of use of PHLIs and constraints respectively. In line with Ammad et al. (2021), all items with factor loadings below 0.70 were dropped during the confirmatory factor analysis (Table 9). The assessment of reliability and convergent validity as shown in Table 10 suggest that the measures meet the 0.7 threshold for Cronbach alpha and composite reliability as well as the 0.5 thresholds for the Average Variance Extracted (AVE). In assessing the discriminant validity, Tables 9 and 11 also illustrate the results for the cross-loadings and the Fornell-Lacker criterion respectively. It can be observed that with the Fornell-Lacker criterion, the correlation between the construct itself is higher than the correlation with other constructs. The cross-loading also shows that items load more heavily on themselves than other constructs. Further, multicollinearity was assessed by using the variance inflation factor. As depicted in Table 13 (Appendix), variance inflation factor ranged between 1.434 and 3.278. This range is within the acceptable range of less than 5 as reported by (Akinwande et al., 2015).

4.5.2 Path analysis

The path analysis was done using Haye's process macro plugin in SPSS. In conducting the path analysis, age, experience and level of education were controlled. These variables were controlled because, the age of an individual could influence the usage of PHLIs, likewise the level of education and experience. These variables could all influence the level of use of PHLIs. As depicted in Table 12, constraints have a negative relationship with usage of PHLIs. This means that usage of PHLIs reduces as constraints increase. The conditioning role of awareness on the relationship between constraints and usage of PHLIs is not significant but the conditioning role of perception on the relationship between constraints and usage of PHLIs is significant. This suggests that as perception of farmers improves (from negative to positive), the negative effect of the constraints reduces to achieve higher usage. Awareness does not significantly moderate the relationship between constraints and usage. This could be due to the fact that awareness does not represent beliefs, hence farmers who become aware of PHIs may also become aware of the constraints which may militate against usage. Perception on the other hand is the way we interpret and organize the sensory information we receive (Conrad et al., 2022). This means that as farmers become aware of constraints, they go ahead to interpret them alongside the expected benefits which in turn influences the usage of PHLIs. None of the control variables was significant.

Table 9: Factor and Cross loadings of the measurement items

Measurement items	Level of use	Perception	Awareness	Constraints
Use of insect-resistant varieties	0.766	0.487	0.288	0.438
Use of hermetic storage	0.776	0.514	0.36	0.482
Use of organic pesticides	0.842	0.554	0.298	0.463
Use of drying sheets	0.855	0.54	0.349	0.462
Use of chemical treatments	0.795	0.46	0.315	0.512
Use of proper transportation	0.762	0.432	0.275	0.455
I feel more confident in investing in my farm knowing that I have postharvest loss technologies to reduce losses and improve profitability	0.45	0.802	0.233	0.518
Postharvest loss innovations have also helped me reduce my environmental impact by reducing waste and increasing efficiency	0.474	0.842	0.25	0.557
I feel proud to be a farmer who is using modern technologies and techniques to improve my farm and community	0.584	0.815	0.268	0.646
I think that postharvest loss technologies should be tailored to meet the needs of small-scale farmers and their specific crops	0.445	0.713	0.285	0.373
I believe that the cost of some postharvest loss technologies is too high for small-scale farmers to afford	0.511	0.81	0.236	0.467
I believe that postharvest loss innovations could greatly benefit our farming community, but we need more education and training to understand and implement them	0.492	0.788	0.227	0.447
By using postharvest loss technologies, we can contribute to the global effort to reduce food waste and ensure food security for all	0.254	0.218	0.755	0.327
Postharvest loss innovations can help us store crops for longer periods, giving us more flexibility in when and where we sell them.	0.271	0.298	0.756	0.381
There are many training and educational resources available to help us learn about and implement postharvest loss technologies	0.337	0.284	0.791	0.363
Using postharvest loss innovations can help reduce losses and increase our income by allowing us to sell more high-quality crops	0.318	0.153	0.728	0.356
Lack of training and education on the use of PHLIs.	0.451	0.399	0.416	0.791
Limited access to financing/source of capital	0.419	0.568	0.324	0.767
Limited access to market demand and market access	0.387	0.445	0.255	0.717
Limited government/policy support	0.555	0.575	0.453	0.851

Table 10: Assessment of reliability and convergent validity

	Cronbach's alpha	Composite reliability	Average variance extracted (AVE)
Level of use	0.887	0.914	0.640
Perception	0.884	0.912	0.634
Awareness	0.753	0.843	0.574
Constraints	0.790	0.863	0.613

Table 11: Fornnel-Lacker criterion assessment

	Level of use	Perception	Awareness	Constraints
Level of use	0.8			
Perception	0.624	0.796		
Awareness	0.394	0.314	0.758	
Constraints	0.586	0.637	0.471	0.783

Table 12: Hypotheses testing

Hypothesis	Paths	Effect	T value	P value
H1	Constraints	-1.7515***	-3.1306	0.002
H2	Perception*Constraints	0.4794***	2.9097	0.004
H3	Awareness*Constraints	-0.0822	-1.5548	0.1214
Control variables	Age	-0.0453	-0.9072	0.3653
	Education	-0.0183	-0.4602	0.6458
	Experience	-0.0636	-1.3938	0.1648

***=significance at <1%

5.0 Conclusions and Recommendations

The descriptive results have revealed an improvement in women and youth participation in maize and cowpea production in the municipality. Consistent with a priori expectation, smallholder farmers interviewed had low level of formal education. The study revealed that the three most patronized postharvest loss innovations (PHLIs) amongst farmers in the municipality were the use of moisture meters, warehouses and the use of mechanical threshers.

The major sources of information on PHLIs for smallholder farmers were found to be radio broadcast (35.9%) and information centres at the community level (27.8%). The study has provided evidence to show that awareness level about postharvest loss innovations among smallholder farmers was generally low. However, among farmers who were aware of the innovations, perceptions were positive. The major challenges to the use of postharvest loss innovations in rural Ghana were inadequate storage and road infrastructure, limited access to financing and lack of government/policy support. Results from the path analysis revealed that awareness level of farmers about PHLIs had no significant conditioning or moderating effect on the constraints to the usage of PHLIs. However, farmers' perceptions on PHLIs had a significant moderating effect on reducing the negative influence of constraints, thereby promoting usage/adoption of PHLIs.

Based on the key findings from the study, the following recommendations are made:

- I. Awareness levels of farmers on postharvest loss innovations should be improved through periodic education and sensitization by the AEAs through local radio stations and community information centres. The sensitization should also aim at dispelling negative perceptions about innovative postharvest management technologies among farmers to improve uptake of these innovations to improve food security and rural livelihoods.
- II. The central government should invest more resources to complete the uncompleted warehouses started under the One-District-One Warehouse (1D1W) policy, and build new ones to improve access to improved storage facilities across rural districts in the country.
- III. Smallholder farmers should be encouraged by AEAs to form viable Village Savings and Loans Associations (VSLAs) to improve access to credit, thereby stimulating adoption of innovative postharvest management technologies.
- IV. Since awareness and perceptions levels about innovations change over time, any future study on the subject should follow a longitudinal approach instead of the cross-sectional design employed for the current study.

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Appendix

Table 13: Variance Inflation Factor (VIF) of the measurement items

Measurement items	VIF
Use of insect-resistant varieties	1.857
Use of hermetic storage	1.868
Use of organic pesticides	2.653
Use of drying sheets	2.676
Use of chemical treatments	2.328
Use of proper transportation	2.168
I feel more confident in investing in my farm knowing that I have postharvest loss technologies to reduce losses and improve profitability	2.645
Postharvest loss innovations have also helped me reduce my environmental impact by reducing waste and increasing efficiency	3.278
I feel proud to be a farmer who is using modern technologies and techniques to improve my farm and community	2.285
I think that postharvest loss technologies should be tailored to meet the needs of small-scale farmers and their specific crops	1.809
I believe that the cost of some postharvest loss technologies is too high for small-scale farmers to afford	2.303
I believe that postharvest loss innovations could greatly benefit our farming community, but we need more education and training to understand and implement them	2.019
By using postharvest loss technologies, we can contribute to the global effort to reduce food waste and ensure food security for all	1.681
Postharvest loss innovations can help us store crops for longer periods, giving us more flexibility in when and where we sell them.	1.558
There are many training and educational resources available to help us learn about and implement postharvest loss technologies	1.751
Using postharvest loss innovations can help reduce losses and increase our income by allowing us to sell more high-quality crops	1.434
Lack of training and education on the use of PHLIs.	1.676
Limited access to financing/ source of capital	1.598
Limited access to market demand and market access	1.445
Limited government and policy support	1.867

