Technological and economic catch up in the biotechnology sectoral innovation system in South Africa

Ghaneshree Moonsamy

A research report submitted to the Wits Business School in the University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Management in the field of Innovation Studies

Johannesburg, 2024

ABSTRACT

Based on the global drive to move towards knowledge-based economies, several countries have identified biotechnology as a sector of interest for economic development. South Africa too, has identified this sector as a means to stimulate economic growth, bridge the inequality gap and reduce unemployment. Despite significant efforts to date, the impact and performance of the biotechnology sector on the socio-economic status of South Africa has been uninspiring. This study aims to evaluate the existing biotech-based sectoral system of innovation and assess potential pathways that may be undertaken to achieve technological and eventual economic catch-up by the country. Windows of opportunity that may entail technological, demand and institutional/public policies were also evaluated. This study used a mixed method approach, which firstly assessed the performance of the South African biotech sectoral system of innovation (SSI) in comparison to five other countries of interest. Thereafter, semi-structured interviews were conducted with 20 participants involved in the biotech triple helix system of innovation. Key findings indicated that South Africa performed poorly in comparison to other countries evaluated, which included the USA, Germany, Mexico, India and Singapore. Regardless of having pockets of excellence and enabling mechanisms such as supporting policies and available infrastructure, organisational capabilities and a highly fragmented national system of innovation are major limitations of the sector. These findings present a key message in that further, significant efforts are required to build on existing capabilities such that the country is able to increase its global standing in terms of biotech-based innovation. As a developing, upper middle income county, South Africa is unfortunately way of the mark in terms of economic catch up, however pathways of catch-up, specifically technology, demand and policy windows of opportunity do exist and need to be harnessed.

KEY WORDS

Sectoral Systems of Innovation, National Innovation System, Latecomer firms, Windows of opportunity, Biotechnology, Catch up, Middle-income trap, Science, Technology, Innovation (STI), bio-based technologies, Economic development, South Africa

DECLARATION

I, Ghaneshree Moonsamy, declare that this dissertation is my own unaided work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in the field of Innovation Studies at the Wits Business School in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other University.

Signature: ……………………………………………………..

On this ……26th……………… day of ………May ……………………2024………..

Ghaneshree Moonsamy

Name

DEDICATION

This thesis is dedicated to my girls Divya Moodley, Yuvarya Yara Moonsamy and Kareena Nardhamuni as a testament of my love to you. May you three also endeavour to light up the world with your passion and purpose.

ACKNOWLEDGEMENTS

Firstly, I would like to thank God for guiding me through this remarkable journey of life and post graduate study.

I also would like show appreciation to my family for their kindness, understanding and support during the tenure of my study. These past two years have been beyond challenging aside from the onset of a global pandemic, however, we have persevered and shown true resilience. I appreciate you all.

I would also like to thank my supervisor, Dr Ogundiran Soumonni for his guidance and support throughout my research journey in this exciting field of innovation studies.

My heartfelt appreciation also goes to my EPIC employer, the Council for Scientific and Industrial Research (CSIR) for supporting my aspiration in undertaking this study.

To my friends, classmates of MMIS 2019 and extended family, thank you for your motivation, support, understanding and continuous encouragement.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS & ACRONYMS

4 IR	Fourth Industrial Revolution
AI	Artificial Intelligence
APAP	Agricultural Policy Action Plan
A*STAR	Agency for Science, Technology and Research
ARC	Agricultural Research Council
B2B	Business to Business
BERD	Business expenditure on R&D
BIDC	Biomanufacturing Industry Development Centre
BIDF	Biorefinery Industry Development Facility
BRIC	Biotechnology Regional Innovation Centres (BRICs)
CeSTII	Centre for Science, Technology and Innovation Indicators
CIPC	Companies and Intellectual Property Commission
CSD	Central Supplier Database
CSIR	Council for Scientific and Industrial Research
DFI	Development Funding Initiatives
DHET	Department of Higher Education and Training
DSI	Department of Science and Innovation
DST	Department of Science and Technology
DTIC	Department of Trade, Industry and Competition
EDB	Economic Development Board
EFSA	European Food Safety Authority

EMM Emerging Market Multinational firms

EU European Union

FDA US Food and Drug Administration

FDI Foreign Direct Investment

GCIS Good Country Index

GDP Gross Domestic Profit

GMO Genetically modified organisms

GNI Gross National Income

GOVERD Government intramural expenditure on R&D

ICT Information and Communications Technology

IDC Industrial Development Cooperation

IoT Internet of Things

IP Intellectual Property

IPAP Industrial Policy Action Plan

IPO Initial Public Offering

IPR Intellectual Property Rights

IS Innovation System/s

IT Information Technology

KRISP Kwazulu-Natal Research Innovation and Sequencing Platform

KZN Kwa Zulu Natal

LCF Latecomer Firms

M&A Mergers and Acquisitions

MIT Middle Income Trap

MNC	Multinational Corporation
MNEs	Multinational Enterprises
MRC	Medical Research Council
NACI	National Advisory Council on Innovation
NIC	Newly Industrialised Countries
NIPMO	National Intellectual Property Management Office
NSI	National system of Innovation
OECD	Organisation for Economic Cooperation and Development
PPPFMA	Preferential Procurement Policy Framework Act
R&D	Research and development
ROI	Return on Investment
S&T	Science and Technology
SAHPRA	South African Health Products Regulatory Authority
SMMEs	Small, Micro and Medium Enterprises
SPII	Support Programme for Industrial Innovation
SSI	Sectoral System of Innovation
STI	Science, Technology and Innovation
TIA	Technology Innovation Agency
TLIU	Technology Localisation Implementation Unit
TTO	Technology Transfer Office
TVET	Technical and Vocational Education and Training
UCT	University of Cape Town
UK	United Kingdom

UKZN	University of Kwa-Zulu Natal
UP	University of Pretoria
US	United States
USA	United States of America
VC	Venture Capital
Wits	University of the Witwatersrand

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

1.1. BACKGROUND OF THE STUDY

The biotechnology sector in South Africa has been earmarked as a potential opportunity to stimulate economic growth, bridge the inequality gap and reduce unemployment in the country (Cloete, Nel, & Theron, 2006; DSI, 2019; NACI, 2019). Despite significant capital, financial investment of approximately ~ R1 billion within the period between 2003 to 2011), coupled to the support received from government in terms of policy, the impact of the biotechnology sector on the socio-economic status of the country has been somewhat lacklustre (NACI, 2013; Patra & Muchie, 2017).

South Africa is categorised as one of six African upper-middle-income economies, Africa's second-largest economy, and is considered a latecomer country (World-Bank, 2010). Despite historical injustices that were thrust upon the country, the biotechnology sector in South Africa may provide windows of opportunity to its latecomer firms (LCFs) and by consequence stimulate economic growth which will enable the country to overcome the middle-income trap (MIT) (Guo, Zhang, Dodgson, Gann, & Hong, 2016; Lee, 2013; Lee & Mathews, 2013; Mathews, 2002).

In these types of emergent sectors, LCFs have more windows of opportunity to achieve technological catch-up, but they are more likely to succeed through demand or policy windows in relatively stable sectors or during stable periods in industrial innovation (Guo et al., 2016). A firm's R&D efforts, learning, absorptive and global innovation capabilities form the crux of its independent technological capability (Guo et al., 2016). Although technological capabilities enable latecomer firms to forge ahead, as seen in a few case studies of biotech firms in South Africa, it is more the intangible globalisation capability that either enables or prevents catch-up. South Africa has been characterised as an emerging market, but its structural challenges have been characterised as severe, limiting, complex and perhaps even insurmountable (Watson & Krishna, 2019). Different strategies may be employed when LCFs embark on global expansion, which may include standardised management and operational practices; supply chain, logistics, talent and human resource management, financial systems as well as corporate governance (Guo et al., 2016).

Western countries are still dominant players in the biotechnology sector, and LCFs in South Africa need not only introduce their goods and services into the global markets but are also required to integrate their technologies and move up the global value chain (Guo et al., 2016). Firms in developing countries that have government support, can enter into mergers and aqcuisitions (M&A) to obtain strategic assets in order to enable them to skip stages and become leading entities. It is therefore key for South African biotechnology firms to develop their global capabilities by increasing their organisational capabilities (Guo et al., 2016).

Successful cases of economic catch-up, whereby lower-middle income countries have progressed to upper-middle income countries are the cases of Singapore, China, South Korea and Taiwan in the Far East and Mexico, Chile and Uruguay in South America (Nelson, 2004; Spillan & Rahman, 2020). In using a similar approach; but retrofitted to the local context, South Africa may be able to achieve similar success, if appropriate and well-constructed strategies for its biotechnology-based firms are drafted and then implemented.

This study focuses particularly on South Africa's biotechnology-based sector including LCFs and their respective technological and organisational capabilities and assesses their potential to seize various windows of opportunity for catching up. A comprehensive assessment of this sector would enable the identification of constraints and enabling factors that would provide a deeper understanding of mechanisms through which bio-based technology development may stimulate science, technology and innovation-based (STI) economic catch-up in South Africa.

1.2. CONTEXT OF THE STUDY

Economic "catch up" refers to the ability of low to middle-income countries to stimulate and boost their economies in a sustained manner (Lee, 2013; Soumonni, 2014). When these countries are able to achieve middle-income status, it is not guaranteed that they can then attain high-income status. "Catch-up", a macroeconomic term, refers to the degree to which different countries that were significantly lagging behind the frontier at the commencement of a known period, but were able to reduce the productivity gap in terms of per capita income with these frontier countries upon cessation of specified time period (Malerba & Nelson, 2011).

Technological catch-up does not refer solely to activities that encompass machines, or other physical structures, in the engineering sense of the term. It is further extended to include aspects of macro-and sectoral level organisation, as well as a cohesive and coordinated management of activities at these levels (Nelson, 2004). In many regions, particularly in the African context, organisation and management of these activities are more difficult to master in comparison to the engineering aspects (Nelson, 2004).

Furthermore, in these more complex settings, the ability to learn and acquire existing capabilities are required to enable a change in the economic system (Malerba & Nelson, 2011). In emerging countries, technological capabilities must include both the creation of new knowledge as well as their applications to address both the economic and social problems that may exist in a particular context (Archibugi, Denni, & Filippetti, 2009). It is also essential to ensure that the sectoral system framework which entails the structure, nature, organisation, as well as the innovation dynamics and sectors of production in a particular country is well understood (Malerba & Nelson, 2011).

The approach used for technological and economic catch up may include an integrated approach of either technologies, or products (related or unrelated), firms and organisations; or the replication of technological aspects which include imitation and selection of certain avenues of pursuit, such that inefficient or ineffective utilisation of resources is minimised (Malerba & Nelson, 2011). The processes of technological learning are only a minor component of innovation-based catch-up, and other facets of a nation’s institutional structures include: (i) its actors, (ii) its existing knowledge base, and (iii) its institutions (Malerba & Nelson, 2011). Some key criteria required to enable the systematic aspect of economic catch-up includes (i) the level of a country’s education and training systems, (ii) its human capital sector (labour and capital markets); (iii) its degree of competition or competitiveness, (iv) its regulatory policies, (v) provision of infrastructure support, and (vi) the ability and responsiveness of the government of a country to facilitate and support rapid yet sustainable economic development (Nelson, 2004). Institutions are important in this context as the building of these new institutions is capital-intensive, and the adaption of the historic ones towards new initiatives is the most challenging aspect of the catch-up process (Nelson, 2004).

Technological spill-overs are the main source of innovation in emerging markets, and as a result of secondary innovation, LCFs tend to follow the same trajectory as developed country firms and are not able to leapfrog to then become frontier firms (Guo et al., 2016). This "path-following" mechanism occurs as a result of two major disadvantages, in that they are dislocated from independent R&D conducted by industry as well as the global market (Guo et al., 2016).

In 2019, the National Advisory Council on Innovation (NACI) of South Africa commissioned a report to list specific areas of Science, Technology and Innovation (STI) that are robust and are at present, working well in South Africa (The SAForSTI report). This report outlined the areas that have a high potential for growth, as well as the areas that are somewhat new to the country and continent (DSI, 2019). The areas include nutrition and water security, Information and Communications Technology (ICT), circular economy, education, energy, the future of society, and high tech industrialisation (NACI, 2019).

Inasmuch as these areas of focus aim to address the key challenges faced by the country, the country is part of a global village. As a result, it is striving to develop enabling technologies, which include artificial intelligence (AI), robotics, machine learning, the Internet of Things (IoT), additive manufacturing, nanotechnology, and biotechnology. These enabling technologies form aspects of a new production revolution also termed the Fourth Industrial Revolution (4IR), which, potentially has the ability to transform entire industries and economies, and correspondingly, address the grand challenges of inequality, poverty, unemployment, food and water security, delivery of healthcare, education as well as climate change (DSI, 2019; NACI, 2019).

Both developed and developing countries have varied views on 4IR due to both the opportunities and threats these advancements impose on society. However, despite the impact ,the new technological revolution may have on employment statistics, unlike Western countries, a wealth of opportunity is possessed by African countries as their youth population may serve as a catalyst in the context of rapid technological development and socio-technological transformations associated with these new technology paradigms of the 4IR (NACI, 2019).

In this context of global advances in biotechnology, this study aims to unpack the sectoral innovation system of biotechnology in South Africa, together with its LCFs and existing technological capabilities, which includes its knowledge and technologies, actors and networks, and institutions (Malerba, 2005). Furthermore, the nature of the linkages and interactions of all the respective actors were also be interrogated. This study could further propose a process-oriented method which could initiate and guide South Africa's biotechnology-based emerging market multinational firms (EMMs) to identify issues that prevent catch-up, delineate the complexity of the sector, and uncover potential patterns of strategies used by other "catch-up type" multinational enterprises (MNEs) in response to windows of opportunity (Guo et al., 2016).

Globally, the United States of America (USA), Spain and France are the top three leading countries in terms of biotechnology firms. In 2015, these countries were reported to have had 11 367, 2831 and 1950 biotech-based firms respectively (Phillips, 2019). These top three countries are followed by Korea, Germany, United Kingdom, Japan, Mexico, New Zealand and Belgium. Of these top 10 listed companies, Mexico is the only upper-middle income economy (GNI per capita between $3,996 to $12,375) listed with ~180 firms that are actively involved in either the development or use of biotechnology in agriculture (31%), environmental applications (23%), healthcare (18%), food (18%) and others (10%) (BIO, 2010; World-Bank, 2010)

There are different approaches used to examine the dynamics of a particular sector (i) assessment of market structure and innovation, (ii) evaluation of learning conditions and technological context, and (iii) assessing sources of innovation and the mechanisms of appropriability in a particular sector (Malerba, 2005). Furthermore, Malerba (2005) presented a complementary framework referred to as the sectoral system of innovation approach, which was devised on the basis of evolutionary theory and the innovation systems approach. This approach assessed the rate and type of innovation in a sector as well as the organisation of its related innovative activities.

In principle, South Africa has in place, several initiatives that would typically enable a thriving biotechnology industry. These include national strategies, such as the

National Biotechnology Strategy, the updated White Paper for Science, Technology and Innovation, as well as the Bioeconomy strategy (DST, 2013; DST, 2019; South Africa. Department of Arts & Technology, 2001). These strategies focus on the development and use of agriculture, industrial, health and environmental bio-innovation. However, metrics used to enable the monitoring of impact are yet to be developed and as a result, the performance of the industry cannot be elucidated (Bracco, Calicioglu, Gomez San Juan, & Flammini, 2018). Furthermore, the national system of innovation (NSI) in South Africa is somewhat fragmented, from top levels down. At the state level, the Department of Science and Innovation (DSI) is the custodian of all science, technology, and innovation agendas, and creates policies and frameworks specific to the biotechnology sector. The Department of Trade, Industry and Competition (DTIC) manages intellectual property coupled to the commercialisation of biotechnology-based activities (Cloete et al., 2006). This divided responsibility, lack of integration and minimal coordination leads to a fragmentation of efforts that are core to the success of biotechnology-based enterprises in the country. This fragmentation is not only noted at state level, as there is a further disconnect between other key stakeholders including, academia, science councils and other institutions due to conflicts that arise as a result of competition and misalignment to a common purpose (DST, 2013). These weak linkages are not unique to the South African NSI, as this dominant characteristic is common across several countries in the Global South, more specifically in African countries (Arocena & Sutz, 2000; Oyelaran-Oyeyinka, 2014).

1.3. PROBLEM STATEMENT

Many countries have been moving away from traditional resource-based outputs into more knowledge-driven economies, with a greater diversity of goods and services as outputs (Bullinger, Auernhammer, & Gomeringer, 2004; Cooke, 2002; Iizuka & Thutupalli, 2014; Stevens, 1996). As the rate and scope of globalisation increases, economies and companies are now interdependent in terms of exchanging both these goods and services, but more importantly, knowledge (Bullinger et al., 2004). However, an asymmetry of interdependence is evident, as more technologically advanced countries, typically those in the Global North, have wider connections and access to more financial resources than countries lagging behind. Typically, the countries that lag behind reside in the Global South and as a result, developed countries are seldom reliant on these developing countries in terms of their higher-level supply chains (Acemoglu, Robinson, & Verdier, 2017). These countries are, however, somewhat reliant on developing countries for the lower levels of supply chain, such as minerals and other resources. This issue of asymmetric interdependence is a core issue, and developing countries must strive to achieve symmetric or roughly equivalent exchanges in terms of value. If this were not achieved, a deficit in terms of trade and other performance measures would constantly be ensued.

In South Africa, and other developing countries, governments cannot merely benchmark their NSIs to developed countries without unpacking their real differences and intricacies. More importantly, templates and frameworks developed in the Global North cannot be applied simply to South Africa, and other countries belonging to the Global South. Policymakers need to take into account the specificities of the system of a particular country, and must refrain from applying generic, one-size-fits-all policies (Bartels, Koria, & Vitali, 2016; Chaminade & Vang, 2008). South Africa as a country stuck in the MIT (Andreoni & Tregenna, 2021), does not have a specific catch-up policy, unlike South Korea, Taiwan, and Singapore. The country has, however, identified biotechnology as a sector that is of strategic importance for bio- and general economic development (DSI, 2019; Mroczkowski & Elms, 2009). Intentional catch-up, in terms of both its economic and technological dimensions, cannot happen inadvertently, and in order to achieve this, the state must direct its efforts towards driving entrepreneurship, institutional building, increase domestic production and reduce imports of foreign goods and services (Adebowale, Diyamett, Lema, & Oyelaran-Oyeyinka, 2014).

The biotechnology sector is considered to be a knowledge-driven industry, and biotechnology firms have been found to cluster around knowledge-producing entities, typically universities (Cooke, 2002; Mroczkowski & Elms, 2009). Studies were undertaken globally which focussed on the biotechnology sector noted that governments were aiming to create clusters of regional governance structure. These included the presence of industry, funding agencies, and knowledge centres such as research councils and universities, in order to support regional or sectoral innovation and economic communities to create access to global markets. Several clusters focussed on biotechnology have been investigated in India, Hungary, Korea, Mexico, Poland, Cambridge (United Kingdom), Cambridge (USA), Germany, Massachusetts, and several others (Cooke, 2002; Iizuka & Thutupalli, 2014; Mroczkowski & Elms, 2009).

South Africa itself set up four Biotechnology Regional Innovation Centres (BRICs) in 2002 (Uctu & Essop, 2012). These included the Cape Biotech Initiative, located in the Western Cape, focused on biotechnology-based research and development centred on human health. The Biotechnology Partnership for Africa's Development (BioPAD) was in the Gauteng Province and focused on agricultural, mining, and environmental biotechnology. The East Coast Biotechnology Consortium, EcoBio, traded under the name of LIFElab, which was located in KwaZulu Natal (KZN). LIFElab focused both aspects of human health biotechnology as well as Bioprocessing R&D. PlantBio, also located in KZN at the University of Kwa-Zulu Natal – previously known as the University of Natal, was the last centre to be formed in 2004 and focussed primarily on plant biotechnology-base R&D (Mulder & Henschel, 2003; Uctu & Essop, 2012).

The BRICs were in operation from 2002 to 2009; however, they did not provide the return on investment (ROI) as originally intended. During 2004 to 2007, the South African government had invested ~R450 million into these BRICs for biotechnology R&D, however, due to a lack of performance, these four BRICs were amalgamated into the Technology Innovation Agency (TIA) in 2008, as part of the DSTs Ten Year Plan (DST, 2008; Uctu & Essop, 2012). The rationale for this change in direction is not clearly articulated in the annual reports of the respective entities, and therefore, the reasons that are attributed to the failure of the BRICs cannot be clearly unpacked.

These developments in South Africa's biotechnology landscape, in and of themselves, display the crux of the country's vacillating approach that impedes the biotech sector from competing with other emerging markets (Cloete et al., 2006; Uctu & Essop, 2012). In developing countries, such as South Africa, it is imperative that policymakers understand the structure and nuances of their NSI, particularly in terms of the intricacies that may determine the behaviour of actors and the overall functioning of the NSI. Even though policies to support the development of a bioeconomy are in place in the country, and have been in place historically, both the social and economic impacts of this sector in South Africa cannot be suitably determined.

Studies have found that several actors within the biotechnology sector are included in both the local, sectoral, and national levels. Therefore, it is vital that successful partnerships among the innovators must be facilitated and clusters formed in order to enable the synergy of competencies to offer solution-based innovations, not individual products to increase national competitiveness (Bullinger et al., 2004; Cooke, 2002; Wong, 1999). Currently, the activities of actors within the South African biotechnology sector are fragmented and lack cohesion, as networks that facilitate both vertical and horizontal collective learning and innovation are limited (Cloete et al., 2006; Mulder & Henschel, 2003; Uctu & Essop, 2012). The earlier traditional and linear models of R&D as the basis for innovation have given way to more systemic models which entail a wide-ranging network of sources and actors that have integrating complementary competencies, unlike the previously commissioned BRICs of South Africa (Bullinger et al., 2004; Cooke, 2002; Hobday, 2005). The success of these clusters is dependent on the type of actors present and the model employed within the biotechnology SSI to suit the context of a specific country. Several authors have assessed the varying strategies employed by individual countries and unpacked their levels of organisation, long cycle and short cycle development, appropriability, and cumulativeness (Bullinger et al., 2004; Dosi, 1982; Lee & Malerba, 2017; Lee & Malerba, 2018; Leydesdorff, 2000; Malerba & Mani, 2009; Malerba & Orsenigo, 1995; Park & Lee, 2006).

Due to the nascent biotechnology sector in the country, typical measures of biotechnology performance such as those used frontier economies with respect to that sector cannot easily be transferred. Due to South Africa being a late-industrialising country, factors that were explored in this study included (i) the number and nature of biotechnology companies that are registered in the country; (ii) the value of government spending for biotechnology; (iii) the value of venture capital; (iv) industry funding for biotechnology; (v) the number of researchers that currently work in this sector and (vi) the turnover of the industry as prescribed by the OECD (2018). Other factors included the assessment of the country's number of initial public offerings (IPOs), patents and publications, product pipeline, existing policies albeit for general R&D, Biotech-specific R&D as well as commercialisation activities (Mroczkowski & Elms, 2009; OECD, 2018).

Based on the aspects listed, this research report aims to depict the status of the South African biotechnology sectoral innovation system, and outline potential pathways for the sector to achieve technological catch-up and concomitantly harness the dynamics of the biotechnology sectoral system, which can be attained through technological, demand and, institutional/public policy windows (Lee & Malerba, 2018). This may enable the country to leapfrog frontier nations and may even propel South Africa as one of the world's leaders in a few biotechnology-based products and processes. As part of the association of emerging economies BRICS, comprising of Brazil, Russia, India, China, and South Africa, South Africa may have more success in emulating certain patterns used by these emerging economies to attain catch-up to other mature economies such as those in the Global North. There are several models used by the different countries in terms of public versus private funding, spin-out companies incubated by universities and science councils to venture capital models, as well as the type of biotechnology solutions they intend on developing (Hobday, 2005). This study enabled the determination of the current level of technological capabilities in South Africa, and identify viable pathways that the country could possibly pursue in order to close the productivity gap with other higher-performing biotech sectors in different countries in both the Global North and South. Further items for consideration included the current population and GDP of the country, the ranking of the country according to its World Economic Forum Global competitiveness ranking, establishment and regional location of R&D centres and hubs, R&D outsourcing activities, the number of collaborative agreements that are in place and the number of acquisitions that have taken place (Mroczkowski & Elms, 2009, WEF, 2019).

1.4. SIGNIFICANCE OF THE STUDY

This study is of relevance to all STI-based stakeholders present in the South African NSI, and includes all relevant stakeholders, listing the actors within the triple helix (government, academia, and industry). The findings of this study provided an assessment of the current levels of capabilities with the sector and its potential impact in terms of boosting the troubled South African economy. It may also enable the identification of windows of opportunity that are available locally, such as health, or other social challenges, or global challenges such as developing viral vaccines, pharmaceutical drug targets, and others. The data generated from this study also adds empirical findings that augment the existing body of knowledge. Furthermore, the research methodology and findings presented in this bio-based technology study may be used to identify other sectors of applicability in the country, such as textile and clothing, automotive, defence, and digital banking.

1.5. RESEARCH QUESTIONS

In addressing the problem statement outlined above, this study intends to address the following research questions:

1.5.1. As a late-industrialising country, how does South Africa’s biotechnology sectoral system compare to leading and peer countries in terms of the six identified factors?

1.5.2. What is the status of the countries IPOs, patents and publication output, product pipeline, policy landscape for both general and biotech-specific R&D and commercialisation activities?

1.5.3. What pathways of catch-up may apply to South Africa by harnessing the three windows of opportunity, which include technology, demand, and institutional/policy windows?

1.6. LIMITATIONS OF THE STUDY

This study is limited to assessing the impact of bio-based technologies on development in South Africa and does not extend to other sectors.

1.7. ASSUMPTIONS

There are no study assumptions.

1.8. DEFINITION OF KEY TERMS

Catch up - ability of low and middle-income countries to grow their economies in a sustained manner

1.9. OUTLINE AND STRUCTURE OF THE REPORT

Chapter 1 outlines the purpose of the study and provides a context of which the research aims to address a particular problem/challenge. This chapter also provides insights into the significance of the study and elaborates on its applicability and current context in South Africa, specifically the biotechnology-based sectoral system of innovation. Also covered in this chapter are the delimitations and associated assumptions undertook.

Chapter 2 comprises the literature review for this particular study. It entails the explanation of the concepts of economic development, catch up, and the middle-income trap. It also entails specifics on the South African STI landscape, focussing particularly on the bio-based technology landscape. It also presents evidence for instances whereby windows of opportunity were identified and either technological catch up was achieved, as well as in instances where failed attempts for technological catch up were identified. The case for economic catch-up in South Africa is also presented, and the role, relevance, and contribution of each actor is also reported.

Chapter 3 details the research methodology and includes the research strategy and design, how the participants for the study were identified, how the methods were defined and developed, how data was collected, analysed, and reported, as well as reports on the delimitations and ethical considerations required to conduct this study.

Chapter 4 presents the summary of research findings for both the qualitative and quantitative aspects

Chapter 5 comprises details obtained during the study and draws contrasts with those presented in the literature.

Chapter 6 details the key research findings and presents an outline of current and future perspectives on technological and economic catch-up of the biotech SSI in South Africa.

CHAPTER TWO: LITERATURE REVIEW

2.1. ECONOMIC GROWTH, CATCH UP AND THE MIDDLE-INCOME TRAP

Economies all across the world vary in terms of their productivity levels, the standard of living amongst their citizens, the speed and level of economic development (Lee & Malerba, 2018). The factors that contribute to these differences between low-and high-income countries were not investigated; until after the end of World War II, and historically, included only human capital and countries specific institutional structures.

Schumpeter (1947), states that factors such as physical environment, social organisation, institutions, and technology enhance economic growth. However, these factors do not sufficiently explain economic growth as it is not autonomous, and growth thereof is dependent on several factors outside of itself. To add further complexity, there are differences in views between evolutionary economic theory and neoclassical theory of growth (Nelson, 2008).

As per the neoclassical growth theory, low-income countries have a low level of physical and human capital which is directly related to low levels of productivity and income. As a result, the development of these economies and countries were and are currently constrained (Lee & Malerba, 2018). Frontier countries on the other hand are high-income, have high levels of capital, and have the required institutional structures to maintain their position. Therefore technology transfers in this setting, are not difficult to achieve (Pack & Nelson, 1999).

In industrialised economies, technological capabilities are developed from innovation to investment to production (Robertson & Jacobson, 2011). In late-industrialised countries, the reverse ensues, in that technologies that have been developed elsewhere are transferred into the country. Production capability around the particular technology is then established, and upon successful demonstration of this ability, investment and innovation then arise (Robertson & Jacobson, 2011). Taiwan, Singapore, and South Korea are considered newly industrialised countries (NICs) which have altered the view that late-comer countries needed to follow the path of frontier countries or reverse engineer emerging technologies (Robertson &

Jacobson, 2011). In high tech sectors, latecomer countries may even be able to leap-frog, stage skip, or path create in technology development, as there is no real need for significant capital investment (Lee, 2019; Malerba & Nelson, 2011). In the instance of Information Technology (IT) and electronics industries, several late-industrialising countries have leap-frogged technology development of frontier countries.

The catching-up process in itself describes the phenomenon whereby, a latecomer firm or economy can gain access to a particular advent of technology. These latecomer entities are usually less developed countries and are referred to as technology followers (Lee & Mathews, 2013). This latecomer/emerging entity is then able to master the existing technology developed by a leading entity, and in some instances, leap-frog the incumbent (Fagerberg & Godinho, 2004; Nelson, 2004). This may be done by implementing new technologies, other complementary products, and managerial structures in addition to what was originally developed by the leader. This adaption to the local operating climate almost unequivocally warrants catch-up (Lee & Mathews, 2013). The mechanism in which this occurs portrays the advent of catch-up, and it integral for any latecomer/emerging entity to understand and then apply to achieve innovation-based economic growth.

Apart from the technology aspect per se; organisational aspects are equally vital to ensure that the technology destined for localisation has the necessary enabling environment that promotes the mastering of the particular technology. In this aspect, organisational structures and management approaches are integral to the catch up (Nelson, 2004). It also has been identified that latecomer firms are not required to burden themselves with the excessive upfront research and development (R&D) costs and find themselves at a cost advantage. When they successfully identify a potential technology, they then ensure that knowledge and skills are transferred from the leader countries to the latecomers (Lee & Lim, 2001). It is in this regard, that absorptive capacity becomes integral to the process of catch-up. The absorptive capacity of a nation is characterised by the level of education provided by its educational institutions, as well as the capacity and capability of both its organisations and institutions (Lee & Lim, 2001; van Wyk, 2018).

When catch-up occurs, it occurs in specific sectors of an economy, and a country may demonstrate catch up in only a few sectors of an economy and countries may able show catch up in certain sectors. To demonstrate, India was able to show successful catch-up in the pharmaceuticals sector but not in the production of telecom equipment. Brazil too was unable to catch up in pharmaceuticals but was successful in agro-food processing. When attempting to catch-up a firms learning and capabilities is critical. Firms in developing countries try to unpack and emulate what frontier firms do (Malerba & Nelson, 2011).

2.2. THE MIDDLE INCOME TRAP

Historically countries were divided into low-income (poor) and high-income (rich) counties. More recently, countries are categorised as per their income groups based on gross domestic profit (GDP) per capita. These groups are (i) low income - < $2 000; (ii) lower-middle-income between $2 000 and $7 250; (iii) upper-middle-income between $7250 and $11 750 and (iv) high-income > $11 750 (Felipe, Abdon, & Kumar, 2012). According to data compiled by Felipe et al. (2012) in 2010, there were 40 low-income countries, 38 lower-middle-income, 14 upper-middle-income, and 32 high-income countries. Countries that have classified as being middle income, have to increase their economic growth at a fast rate and maintain this growth in order for these countries to achieve high-income status. If these countries are unable to grow at the required rate, they fall into what is referred to as a middle-income trap (Felipe et al., 2012).

It has been found that economic activities of low to middle-income countries are structured primarily around agriculture (Henderson, Squires, Storeygard, & Weil, 2018). Although this sector creates high levels of employment and outputs in the form of products, it is largely “unproductive”. Upon mechanisation of the agriculture industry in the form of capital accumulation; together with the upskilling of workers, this industry can be transformed to be more high value, as well as provide services other than primary products. Furthermore, these workers then are transferred into other more productive industries which thereby can increase the countries income per capita (Felipe et al., 2012). This ultimately presents the economic development of a country whereby it is able to move resources and capital from low productivity areas such as agriculture to areas that are considered highly productive such as industry and services. These countries need to also invest in enabling capital/infrastructure, which can facilitate industrialisation using new methods of production, which could result in new product development. This intent of economic development is complex and requires changes in social institutions, beliefs other than just urbanisation of the country (Tabellini, 2010).

As of 2010, 35 countries found themselves in a MIT; Europe (2), Asia (3), Latin America (13), Middle East and North Africa (11), and sub-Saharan Africa (6) (Felipe et al., 2012). Countries may find themselves in the MIT based on the structure and diversity of its current economy and could be involved in economic activities that are more low productivity-based rather than high productivity based. Products generated in these MIT countries could be intended for local use and not destined for the export market, or the types of products that are being exported are not of the nature required for specific economic growth and development. Countries that are present in the MIT can graduate from this status albeit from a concerted effort to structurally transform its capabilities and become global competitors or leaders in relevant areas of industry.

Trade data may be used to evaluate how some countries have graduated from the MIT. South Korea and Malaysia are countries that were able to transition from low-middle income to upper-middle income predominantly by changing or diversifying their product export profile, from standard basic products to a bigger portfolio containing more sophisticated products. If countries are determined to overcome the MIT, they need to improve on their productive capabilities which will then create a more diverse product portfolio and also have the competence to develop more complex, sophisticated, and well-connected products (Felipe et al., 2012). The nexus of factors required to overcome the MIT is critical for policymakers to understand, in order to facilitate the countries progression towards high-income status.

2.3. MECHANISMS OF ECONOMIC CATCH-UP

Economic catch-up can be stated as an occurrence of technology localisation. The development of technological innovation within a latecomer nation presents a unique opportunity not only catch-up to frontier nations, but possible leapfrog them to gain certain market dominance (Lee & Mathews, 2013; van Wyk, 2018). This is a critical factor for developing countries to industrialise or even re-industrialise (Bento & Fontes, 2015; van Wyk, 2018).

A majority of developing or latecomer countries have prioritised STI for growth and catch up (Lee & Mathews, 2013). However, to do this, there are several key factors are required by these “catch-up” countries, including access to resources needed for development, as these resources are limited and oftentimes restricted (Lee & Mathews, 2013).

Countries may also decide on a suitable catch-up approach and could either select following the path of others, stage skipping, or the creation of its path. Despite the challenges that developing countries face; these nations have some competitive advantages (Lee & Mathews, 2013; van Wyk, 2018). Nations of this nature should apply their skilled labour and financial resources albeit constrained; to identify current technologies that already exist as they have the freedom to enter emergent industries much earlier. Exorbitant expenses of R&D do not burden these countries and this enables them to generate low-cost-based entry products to potentially mature technology sectors (Lee & Mathews, 2013; van Wyk, 2018).

To successfully initiate the process of technological catch-up, firms within lagging nations, need a technological platform on a minimalistic basis, to develop capabilities for product and process development (Lee, 2009; Lee & Mathews, 2013).

2.4. FACTORS THAT ARE REQUIRED TO ENABLE CATCH UP

To successfully attain and maintain economic catch-up, all actors within the innovation system must understand and appreciate their interdependency. The quality of education as well as the training systems in a country, together with its labour and capital markets directly impact a nations firms and organisations (Nelson, 2004). In a country, the competition and regulatory policies, infrastructure support programs, and government’s ability to provide rapid yet sustainable economic development are equally important. It has been alluded to that the main reason that latecomer nations display levels of productivity and resultant incomes is as due to low or inadequate levels of physical and human capital, apart from the default situation whereby high-income countries have more access and command over high – tech technologies and other practices (Nelson, 2004). Therefore, it is essential to note that although technological learning is imperative in any nation, developed or emerging, it is merely a foreground to the numerous background operations that are required and present within the system (Nelson, 2004).

If an emerging nation makes a concerted effort to drive economic catch-up, the benefits would include a positive contribution to socio-economic development as well as economic growth. This is under the provision that the required support structures are in place to facilitate and enable learning as well as promote the mobilisation of resources (Lee & Lim, 2001). The directive from this is that one needs to understand the reasons/strategy/potential impetus of countries that were deemed to be significantly further away from the technological and economic frontier of developed nations, and how did they catch up? This is the fundamental question of developmental economics (Nelson, 2004). To further unpack this, other latecomer entities may question the approach used by entities that have "caught-up", in that how they have caught up; as well as how could they also catch-up by applying similar yet retrofitted mechanisms. This involves the study of both past occurrences and scenarios as well and the future outlook for these entities (Nelson, 2004).

Several factors can influence economic catch up at both the macro and firm-level. These include (i) learning and capabilities of domestic firms; (ii) access to foreign know-how; (iii) skilled human capital and (iv) active government policy; amongst others (Freeman, 1995; Malerba & Nelson, 2011). The main factors that determines catch-up involve the learning and capabilities of domestic firms, and have proven to be necessary to enable the catching up country to absorb foreign knowledge and technology (Lee & Lim, 2001). It also enables the latecomer to make modifications and adapt the technology to meet the local needs and demands, to produce new knowledge, to generate products and technologies, and ultimately to distribute these potentially superior products (Malerba & Nelson, 2011). To note, capability building and upgrading of skills that enable latecomers to move up the ladder tend to constitute a continuous process that is also incremental in nature (Malerba & Nelson, 2011). However, industries within a latecomer nation cannot achieve this in isolation, as links are present both upstream and downstream of both their customers and suppliers. Lundvall, Johnson, Andersen, and Dalum (2002), emphasised the role of knowledge, and stated that it is the most fundamental resource in the modern economy. This learning can be achieved by either doing (experimentation) or using; by R&D efforts conducted by public or private sector entities and through the exchange of knowledge through learning networks (van Wyk, 2018).

The second factors entails the access to foreign know-how (Malerba & Nelson, 2011). Countries that are actively involved in frontier research make an active effort to develop, learn and master know-how, and latecomer firms should harness this know-how from frontier countries (Malerba & Nelson, 2011). Accordingly, it must be noted that the channels through which this learning, may occur can be attributed to varying scenarios. In some instances, latecomers license in technologies from foreign producers, while others engage in many R&D and production joint ventures with MNEs (Malerba & Nelson, 2011). Seemingly important, is the cross-border flow of people; whereby citizens from a latecomer country go to learn abroad and then upon return apply their learning; or citizens from the leading country come to the latecomer country to serve the role as advisors, and in some instances, they themselves establish a particular industry within the developing country (Nelson, 2004). University study abroad is a particular facet of foreign know-how transfer in particularly in the fields of applied and engineering sciences. This mechanism of knowledge exchange is integral to the catch up process (Nelson, 2004).

As the process of catch-up develops, the latecomer country attempts to have self-sufficiency in terms of training its citizens, such that over time, their scientists and engineers become industry leaders and play roles that are more significant in the international communities, other than acting as absorbents (Malerba & Nelson, 2011). Fagerberg and Srholec (2005) have also shown that when latecomers focus their efforts on the improvement of higher education systems that focus on engineering-based training, and as well as developing indigenous research efforts; they tend to catch up much more rapidly than those that don’t (Nelson, 2004). It has also been found that when a transfer of know-how does not occur, the catching up process can be seriously impaired (Malerba & Nelson, 2011).

The third common factor identified for economic catch up is skilled human capital development (Malerba & Nelson, 2011). It is relevant in sectors depend on skilled labour, new firm creation, and entrepreneurship, such as technologies pertaining to software development and pharmaceutical development and manufacture (Malerba & Nelson, 2011).

Active government policy is another key factor that can stimulate learning and capability of a nation (Malerba & Nelson, 2011). By taking a hands-off approach, loosen the legislative burden, and becoming an enabler, governments have been able to intervene directly in different areas, such as creating specific R&D programs, establishing credible research organisations, provide research and training at universities, as well as support and enable public procurement within the national innovation system (Malerba & Nelson, 2011).

Once government actively leads development, and facilitates private-public collaboration, a higher level of impact is achieved (van Wyk, 2018). In other aspects, policies pertaining to competitive tendering may also assist and benefit the local economy; however, the government must drive this prerogative. Furthermore, the government could also prioritise supportive policy that is centred on its expansion efforts into industries wherein shorter technology cycle times are required, or efforts are made into segments that are higher in value. Import substitution is an ideal approach for governments to take, especially with regards to high value-added segments wherein manufacturing of products used in a process is done outside of the country and are imported by the latecomer nation at an exorbitant cost; referred to as an ‘oligopolistic market structure’ (Lee & Mathews, 2013; van Wyk, 2018).

Key initiatives that should be driven by various government agencies would be to assist local firms in technology acquisition, as well as land and finances. They can also assist by cajoling the local market to use local products through R&D subsidies and tax (Lee & Mathews, 2013; van Wyk, 2018). Governmental agencies of latecomer nations play an important role in capability building of its latecomer firms. To compensate for the gaps that may exist in prioritised industries, a coordination of activities by industry is required. This may be done by providing the required finance and ensuring access to knowledge to the firm (van Wyk, 2018).

These four factors, when applied in a systemic manner instead of in isolation, brings about a multiplier effort in terms of impact when specific sectors are targeted (Malerba & Nelson, 2011). Other key factors include education at primary and secondary levels, public research system, and universities in a nation. Universities and public research centres are key role players for basic and applied research (Malerba & Nelson, 2011). Currently, R&D that is undertaken in these institutions, plays an important role in a countries innovation systems in terms of catch up, more so now, than in previous years (Nelson, 2004). Creative solutions may be identified by the means of public research, and enables the R&D team to skip stages of development, thus further enabling the catch-up process (van Wyk, 2018).

The presence of and structure of financial systems and other institutions provide support for innovation, production, and diffusion of technology, within a latecomer nation (Malerba & Nelson, 2011). However, the development of a functional NSI, building new institutions, may be required, or old institutions may need to be adapted to suit the changing needs of a country. This instance may prove to be one of the most challenging aspects of the actual catch-up process (Nelson, 2004). Malerba and Nelson (2011), states that actions, interactions, and cognition, of actors is influenced by its institutions, and may include routines and established practices, laws, habits, standards, and norms. These institutions may include enforcement agencies to those that stimulate and create interactions and could include contracting authorities, to patenting entities (Malerba & Nelson, 2011).

Lee and Mathews (2013) emphasises that effective IP regulation is an integral aspect of learning within firms, especially, those in middle-income countries. Furthermore, these governments should be provided with more flexibility in terms of intellectual property rights (IPR) such that local firms have a chance to catch-up. Each country can design a personalised strategy that generates benefits. One approach that may be taken involves a patent combination approach, wherein patent rights can be shared across various local industries and technologies (Lee & Mathews, 2013). Another strategy could entail the use of a utility models system in addition to their conventional invention patent system (Lee & Mathews, 2013; van Wyk, 2018). Similar to infant industry protection and relevant subsidies, conflicts between leading and latecomers' countries tend to emerge more significantly when the catching up entity encroaches onto the international markets. This sometimes includes the export of goods and/or services to the home market of the company which initially held the patent rights (Nelson, 2004).

Entrepreneur acceleration and incubation initiatives are imperative to ensure that entrepreneurs have access to skills, resources as well as capital equipment, which are all important in an innovation-based environment. The primary role of a government is to provide support, particularly financial support in conduct initial phases of R&D that typically has high degrees of uncertainty and is deemed risky to entrepreneurs and SMMEs. Government support of local industries may be provided by promoting preferential procurement of goods and services from local industries. Additionally, by implementing import tariffs to regulate the local market can be endorsed, to promote support of the industries. Tax breaks may be used as an incentive to attract prospective firms and entrepreneurs, local product and service users can also be incentivised when the opt to use locally made products. Governmental organisations are not known for their efficiency, and private-public collaborations can be used to address and implement solution for improvement (van Wyk, 2018). These interventions may assist with accountability and transparency, and also provide insights to government which may facilitate better decision making. Governments of emerging nations should aim to form partnerships with multinational corporations (MNCs), such that these entities can provide infrastructural investment and develop relevant skills. International trade shows can be used to promote awareness of the capability of local firms on a world stage (van Wyk, 2018). These interactions may also create additional opportunities for local SMMEs which may be appointed as subcontractors. Furthermore, there are considerable benefits of knowledge and skills development associated with transnational learning. However, some risks remain in terms of an outflow of young talent in exchange programmes wherein emigrants do not return to their country to birth, which is termed “brain drain”.

2.5. INNOVATION SYSTEMS

The evolutionary economic theories focus on the concepts of national and sectoral systems of innovation. These theories are associated with innovation processes and the dynamics thereof. The key elements linked to economic transformation include learning and capability development which influences potential changes in a particular economic system (Malerba & Nelson, 2011). This infers that heterogeneity in the experience of actors within the system, influences their differential performance and the evolutionary approach entails the processes of variety creation with respect to technologies, firms, products, as well as organisations. In addition, it includes replication and imitation; which influences the continuation of the process of economic development; as well as selection; which refers to the reduction in the variety of economic systems and discourages both ineffective and/or inefficient use of resources (Dosi, 1982; Malerba & Nelson, 2011).

These innovation-based systems and inherent activities bring about innovation-based economic growth. Historical views state that several actors are involved in the national innovation system concept, which in nature is aggregative, and positioned to cover overarching national characteristics (Malerba & Nelson, 2011). These actors referred to herein may include knowledge or research institutes, educational organisations such as Universities and Colleges, industry (all sectors), market-based stakeholder/s, various government departments, and support/special initiative/s (Hekkert, Negro, Heimeriks, & Harmsen, 2011). The networks may operate on a formal or informal basis, such as the linkages between institutions, eg. Industry and university linkages (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; van Wyk, 2018). Due to the dynamic nature of the system; there is an interdependency of the individual components which may influence the trajectory of the innovation initiative as well as the rate of development. This intimate relationship may contribute to the success or failure of the respective innovation system, particularly if one of the components is influenced significantly (van Wyk, 2018).

2.5.1. National systems of innovation

Freeman (1995) and Lundvall (2007) have emphasised the importance of NSI, and that the creation of such a system is what Friedrich List had in mind when he postulated what Germany needed to do in order to get closer to Great Britain and catch up. This was done in the 19th century (Nelson, 2004). However, there was a misconception, that this NSI establishment could only be achieved using key institutions based in technologically advanced countries at or close to the frontier and not necessary in the context of a latecomer nation.

The term “innovation system” informs the design of science and technology policy using a ‘systemic institutional’ approach. Governments cannot merely tick boxes to create the required entities, and thereafter have no role in the actual coordination of these actors and their respective activities. Lundvall (2007) and Viotti, (2015) among others, have highlighted some of the needed re-configuration of the respective NSI, particularly those that exist in the catch-up in the context (Nelson, 2004). Innovation performance is directly linked to institutional setup. This may be in respect to formal institutions that coordinate patenting activities, regulatory frameworks as well as technical standards, and also include informal institutional structures including norms and culture (Laranja, Uyarra, & Flanagan, 2008). It also essential, particularly in our economic climate to ensure that policy is designed to focus on both formal and informal sectors and their institutions (Laranja et al., 2008; van Wyk, 2018). Policy must aim to positively influence knowledge development and interaction and be in sync with 'technological trajectories' (Laranja et al., 2008; van Wyk, 2018).

On a positive note, there are several strategies respective to localisation that can be pursued, however, the size of the local markets needs to be considered. Government should strive to provide access to markets and may be achieved through the promotion of exports. Governments may also consider market protectionary measures, which may include but are not limited to the promotion of government procurement, the implementation of import tariffs, as well as subsidies (van Wyk, 2018).

2.5.2. Sectoral innovation systems

Innovation occurs as a consequence of combining new and old/exiting ideas, which consequently introduces novelty into the socio-economic system (Galindo & Méndez, 2014). Historically, innovation was viewed linearly, in that it was perceived to occur in a stepwise, logical manner which followed in sequence, idea generation, invention, new innovation, and finally the market receives/diffuses the R&D (Godin, 2006). Innovation, as per the definition provided by the OECD is: "*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/Eurostat, 2005). In general, innovation systems consist of three structural components, which are actors, networks, and institutions that work in collaboration towards a common resolution or output (Klein & Sauer, 2016). The components of an innovation system are somewhat interlinked, and when a network is formed, the actors can achieve a common goal of innovation due to knowledge sharing, skills transfer, and "cross-pollination" within and across sectors (van Wyk, 2018).

The systemic innovation model was in intended to address the limitations of the linear model and demonstrated; that at any level; learning goes on within an entity or between actors, and between all collaborators in a specific area or within the project (Taylor & Levitt, 2004). Initially, great interest was expressed solely on the NSI and its related impact on innovation and economic growth. Due to the emergence of innovation frameworks pertaining to the sectoral system, more interest has been generated on this topic, as it provides insight into the interplay between the NSI and SSI of particular regions (Chaturvedi, 2007).

The sectoral level framework refers to the nature, organisation, structure, and dynamics of sector production and innovation (Lundvall, 1992; Edquist, 1997). One can identify the following elements of a sectoral innovation system, which include actors, the knowledge base, and institutions (Malerba & Nelson, 2011). This dynamic view of the sectoral system states that the respective knowledge, actors, and institutions may evolve, as new types of actors may appear, additionally, new vertical and horizontal linkages may arise. As a result, interdependencies may form among industries and technologies as new actors enter the environment (Malerba & Nelson, 2011).

In sectoral innovation systems respective to firms, entrepreneurs can innovate and these innovations create an impetus for other entrepreneurs to follow suit during their operations, and ultimately, more innovations are created (Galindo & Méndez, 2014). The link between entrepreneurship and innovation has also been unpacked to further understand complex innovation systems. Drucker (1998) stated that innovation is key with respect to entrepreneurship activity, and as a result, promotes business creating feedback effects. Domestic firms that are found in emerging or developing nations are not able to compete with imported products from big multinational entities (MNEs) as a result of several resource-based limitations (van Wyk, 2018)

Furthermore, due to several failures linked to collaboration and/or markets coupled to the asymmetrical nature of information flow, technical capabilities that are required for innovation are limited. In general terms, ‘catch-up” is a process of learning, and it may require a long time. Furthermore, the process differs significantly across the various economic sectors within a nation, and the individual factors may lead to either instances of success or failures (Malerba & Nelson, 2011).

In the advent of globalisation, innovation is considered a competitive weapon, and firms and their support structures, are becoming more knowledge-intensive (Cooke, 2002). Cooke (2002) described the following characteristics of biotechnology-based local innovation systems based in Europe. This study found that in this region, countries had developed extensive regional and national relationships, and decision-making powers remain at the regional level. All firms despite their size try to increase the quality of the product while reducing costs and aim to increase competitiveness by addressing organisational innovation. These European firms rely on local supply chains and indigenous knowledge to innovate products and processes.

These European-based clusters have highlighted and acknowledged the importance of the actors within each cluster. These clusters include universities, research institutions, consulting entities, and technology-transfer agencies that are linked to the generation, development as well as supply of new knowledge (Cooke, 2002).

Vertical and horizontal networks are especially important for smaller firms within a cluster in order to facilitate and enables innovation and collective learning (Cooke, 2002). Policies within these regions are being developed to create support for the creation of economic communities, at a regional level, within a multilevel governance structure. This assists the clusters to develop access to global markets (Malerba & Nelson, 2011).

Like the European initiatives, the Indian government was also instrumental in drafting new policies and regulations to make India a reckoning force in biotechnology-based drug development. This enabled the country to be world leaders in terms of both new drug and generic development by amending the existing policy and regulatory landscape (Chaturvedi, 2007).

Each country has a level of uniqueness, and sectoral economic development acknowledges that countries operate differently due to the indigenous process of learning. These factors are dependent on how product mixes differ, the operating model of firms as well as the differentiation of their target markets (Hobday, 2005; Malerba & Nelson, 2011). Catching up does not refer to copying or cloning, and if catch up occurs, it rarely mirrors the efforts of model or frontier countries. Due to the intricacies of specific countries, catch up cannot be attain by copying, and efforts need to be modified such that the specifics of the indigenous circumstances are accounted for. Consequently, according to Schumpeter, innovation in this sense occurs when a break from the ways of doing things, in a more traditional sense, is applied (Hobday, 2005; Malerba & Nelson, 2011). Evidently, these catch-up processes are in many instances not novel per se, but they are indeed new to the country of interest. This usually is plagued with several risks, and takes a significant trial and error effort before learning is realised and draws impact (Hobday, 2005; Malerba & Nelson, 2011).

Firms within a particular country operate under different circumstances. Primary and secondary education, the local universities, its public research system, and government programs are the primary economic factors that may influence innovation systems. They may either directly support or hinders economic activity and innovation (Nelson, 2011). Another pivotal factor is the labour market and the structure of financial systems (Malerba & Nelson, 2011).

For a latecomer innovation system to gain market access achieve sustainability, significant effort is required to "unseat" more established technological regimes. Emerging countries may only achieve this if they provide institutional support for their firms (Kukk, Moors, & Hekkert, 2016). Manessah, Teresa, & Kerrin, (2015) states that national culture that is specific to the country is enforced, combined with associated policy and regulatory frameworks, will display support for scientific development in the field of biotechnology by a particular government. Government is able to support the latecomer firms by presenting access to markets, or by providing subsidies and may apply protection measures to create niche areas as well as assist with R&D efforts (Lee & Lim, 2001). Other innovation policies that may entail other supply and demand factors may also be considered to suit the indigenous environment (Kivimaa & Kern, 2016; van Wyk, 2018).

Technological innovation in a developing country can provide great benefits and should be prioritised to achieve both economic and social development (Lee &

Mathews, 2013). The firms that operate in the latecomer countries experience significant challenges that may include but are not limited to; asymmetry in access to information, inability to access markets, lack of collaboration support and an influx of import products which hinders their ability to be competitive (van Wyk, 2018). Additionally, skills transfer and learning that essentially fosters innovation is suppressed, and may block the creation of export avenues (Szczygielski, Grabowski, Pamukcu, & Tandogan, 2017). Ideally, industrial and innovation policies must be cohesive to attain the required structural and institutional changes which may advocate skills and knowledge generation of firms (Warwick, 2013). Government must work closely with industry in order to create an environment whereby strategies are aligned, and the efforts of all actors are synergistic in nature (van Wyk, 2018). This indicates the essential role of governments in ensuring that local SMEs and entrepreneurs have protection until they reach a readiness level and can compete directly with MNCs. Policy intervention that provides market access, both foreign and local, and an environment that facilitates learning is essential for success (van Wyk, 2018; Warwick, 2013).

The role of financial institutions is relevant in this process as entrepreneurs require financial resources to conduct activities and to finance innovations. Therefore, adequate policies that intends on increasing savings is imperative in facilitating the credit process (Galindo & Méndez, 2014). In addition, the social climate within a country is important in stimulating entrepreneurial activity as well as facilitating the introduction of innovations. These reductions in social stresses would encourage entrepreneurs to persevere and carry out their activities. The measurement of this factor is vital, and the distribution of income distribution is the most representative variable pertaining to this concept (Galindo & Méndez, 2014).

The feedback effect that includes economic growth, innovations, and entrepreneurship, as well as the consideration of certain indigenous factors influences the economic development. Increased entrepreneurship activity and innovation efforts can positively influence economic activity, and these combined efforts must be systemically driven to realise catch up success (Galindo & Méndez, 2014).

2.6. WINDOWS OF OPPORTUNITY

Windows of opportunity is a phrase used to describe the emergence of new technology paradigms, usually in latecomer firms or nations. These windows of opportunity may enable latecomers to catch up or leapfrog incumbent firms or nations (Guo et al., 2016). As part of the catch up cycle, these windows of opportunity may arise from technology, market demand, and policy or institutions in a sectoral system (Guo et al., 2016; Lee & Malerba, 2013).

The actors in a particular sectoral system and their associated actions and interactions determine patterns of catch up. The following factors have been identified as windows of opportunity for catch up: (i) technological windows opened up by emerging technologies and disruptive innovations, (ii) market windows opened by demand shocks along waves of business cycles (iii) policy and institutional windows opened by policy interventions and institutional changes (Guo et al., 2016).

To achieve the desired catch up effect by latecomers, both nations and their firms must attempt to unpack and understand the mechanisms of how each window is created or opened; as well as the process in which latecomers seize the window of opportunities. Firms and nations alike must assess both globalisation and technological capabilities and system interdependencies (Guo et al., 2016).

Numerous literature sources have identified technological spill-overs from incumbents as a critical source of innovation in emerging nations that impacts their technological catch up (Guo et al., 2016; Hobday, 2005). For emerging nations to not only match the technological level of frontier nations, they also need to overcome the disadvantages of being cut off from global knowledge sources for independent R&D and industry-level innovation as well as form connections in the mainstream global market. (Guo et al., 2016; Hobday, 2005).

Lee and Malerba (2018) stated that there four aspects that need to be assessed when evaluating economic catch up by latecomer nations. These include (i), assessment of the sectoral and national innovation systems such that market and system failures may be elucidated; (ii) evaluation of capability building and learning in niche areas and area of specialisation; (iii) catch up may be enable by harnessing diverse widows of opportunity which enable latecomers to leapfrog over their incumbents; and (iv) the understanding the longer perspectives of catch up cycles, whereby new entrants overtake incumbents and then pass on their leadership status to “new-er” entrants.

2.7. THE CONTEXT OF SOUTH AFRICA AND ITS SPECIFIC SOCIO-ECONOMIC CHALLENGES

South Africa is located at southern tip of Africa, and is ranked 47 out of 153 countries, in the Good Country Index (GCIS, 2018). The population of the country is ~58 million and is listed as the most unequal society in the world (Beaubien, 2018). The South African Government has to date implemented various development strategies to decrease the number of South Africans living below the national poverty line. However, this number has increased since 2011 (Beaubien, 2018). In South Africa, it is estimated that ~55.5 percent or more than 30 million people were surviving on less than $5 a day, and unemployment has risen to ~29%, the highest rate it’s been since 2003 - based on 2015 data (IOL, 2019). The key economic sectors of the South African economy include mining, transport, energy, manufacturing, tourism, and agriculture (GCIS, 2018). Several other sectors have been identified as potential areas for growth, which may equip the country to attain economic catch up.

Upper-middle income countries, including South Africa, have already acknowledged the role of STI in driving economic growth. Hence, the government of South Africa has drafted the necessary policies such as the new White paper on Science, Technology, and Innovation, to support R&D-based initiatives that use technology to address social challenges such as poverty alleviations and creating employment (DST, 2019; Harsh et al., 2017).

Governments see these types of emerging technologies as equalising measures in order to bridge the gap of inequality, by training scientists and engineers to develop and promote economic growth in the country (Harsh et al., 2017). This creates the advent of inclusive innovation, and the creation of equity pathways, in that those individuals from previously marginalised backgrounds are provided with the opportunity of participating in the development of emerging technologies. In this way, the country does not become a “dump site” for failed technologies developed in other developed countries or as guinea pigs whereby developed countries merely want to use the nation to test their latest innovations (Harsh et al., 2017).

By endeavouring to initiate inclusive innovation, South Africa aims to bridge the gap of inequality and also reduce the impacts of conventional innovation that in many instances exacerbates this gap (Smith, Fressoli, & Thomas, 2014). Furthermore, emerging technologies may be used to address local challenges that are presented in the country and not necessarily be directed at the same markets in developed countries. These technologies may also provide alternate avenues for a latecomer country, such as South Africa, which has a predominantly resource-based economy (Robertson & Langlois, 1995).

For South Africa to attain sustainable economic growth and development, there is a need for the NSI to be directed by the government, using existing policies and institutional structures to enable technological learning and mastery as required by a latecomer nation (Nelson, 2004). In this case, there is no need for the South African government does not need to commence efforts from ground zero, but may be required to ascertain which elements can be extracted from different entities in different areas, and what policies and institutions may have been overlooked within the current economic climate (Nelson, 2004).

In addition to research policy, the South African government should also consider implementing policy that entails infant industry protection for its entities, as it has been shown that many countries that implement these policies can successfully attain catch-up (Nelson, 2004). However, the challenge is to find effective means to protect these infants without compromising the nation’s ability to contribute in terms of the global arena, particularly in the realm of open innovation (Nelson, 2004). A government strategy that includes the promotion of export of goods will stimulate local firms to make investments in capacity upgrades and system development. This will present an opportunity for the country to access foreign currency, which can further stimulate growth (Lee, 2005; van Wyk, 2018)

Other factors, such as national pride, may also influence the South African government to invest in emerging technologies as a means to not only catch-up but also become leaders in a particular technology. Incidentally, there have been several advances made in South Africa, and as a result, the country has been recognised globally as experts in particular fields, such as nanotechnology, stem cell research, and digital laser technologies. These advances have highlighted the ability of the country to lead in the global STI arena (Harsh et al., 2017). Contrastingly, on the other side of these successes, there have been instances whereby system weaknesses have acted as barriers to knowledge development and diffusion (Jacobsson & Bergek, 2006; van Wyk, 2018). Additionally, in terms of the innovation network, the presence of weaknesses or gaps has limited the interaction and transfer of knowledge and regrettably, institutional weaknesses such as misdirected policies and/or actor weaknesses have had severely restrictive effects on economic growth and development (Jacobsson & Bergek, 2006; van Wyk, 2018).

As stated by Lee (2013) and Lee and Mathews (2013), South Africa needs to strategically identify the investment areas wherein it makes logical sense. Areas that may be most applicable include Biotechnology (including pharmaceuticals), Nanotechnology, Additive manufacturing, Fintech, artificial intelligence (AI)/ supercomputing/ Data science, Agroprocessing, Arms/ ammunition/ Defence, as the country has baseline capabilities in these fields.

Additionally, due to the rich levels of biodiversity of the country, the South African NSI can help alleviate both the local and global burdens should be used as an advantage by local actors to develop new products. Oftentimes, indigenous research long has been overlooked, however has been identified as an important element of catch-up in certain fields. This occurs not by a mechanism of simply copy and paste technology and practice in frontier countries but is done by latecomer nations as a direct need to develop technologies suited to the context of the country. With the use of succinct macro-level innovation-based strategies, capabilities and capacity of the actors within the NSI can be harnessed to generate knowledge and innovate. It has been found that in the South African context, existing university structures tend to be both enabling and disabling. However, the development of an effective system of public research and training, can be developed and implemented (Nelson, 2004).

Foreign direct investment (FDI) plays a significant role in the catch up processes (Nelson, 2004). In addition to FDI, there are fruitful partnerships that form between latecomer and frontier entities, and in some instances, latecomer countries can aspire to successfully sell products on a world market provided that their wares are good enough (Nelson, 2004). This may apply to relatively older fields such as in the engineering sciences, as well as more modern fields which include computer science, biotechnology, and immunology (Nelson, 2004).

South Africa as a nation has a fully-fledged NSI, however, its effectiveness or actual potential to realise economic growth and development has not yet been fully realised. The existing NSI contains several entities include the government departments such as DST now DSI and DTIC, world-class universities and research councils such as the University of the Witwatersrand (Wits) and University of Cape Town (UCT), the Council for Scientific and Industrial Research (CSIR), the Agricultural Research Council (ARC) and the Medical Research Council (MRC). Additionally, special initiatives from the government such as the Industrial Development Corporation (IDC), The Innovation Hub, and the Technology Localisation Implementation Unit (TLIU) as well as several industries across economic sectors. A predominant factor that negatively impacts the functioning of the NSI, is that there are no synergistic and common goals set out for development nor co-development among actors (van Wyk, 2018). South African universities are unfortunately very academically focussed and research initiatives, if active at all, are of little value, commercially (van Wyk, 2018). This hinders the functioning of the NSI, as it does not fully maximise its potential with knowledge development in a collaborative manner. Additionally, there is a lack of a cohesive implementation plan that develops industry, and existing incentives such as tax relief mechanisms and similar R&D-based incentives do not fully create the impetus required. This fragmentation of the pockets of excellence results in disjointed impact, due to the lack of collaboration within the local industry, and additionally, mistrust among actors restricts the potential of fruitful collaboration (van Wyk, 2018).

Furthermore, there are several flagship initiatives such as the Bioeconomy strategy of the DSI and the Industrial Policy Action Plan (IPAP) of the DTIC, however, a clear implementation plan that will coordinate activity amongst all relevant actors is lacking (van Wyk, 2018). The availability of funding in a fairly resource-limited nation is a challenge. The lack or inaccessibility of private funding available further exacerbates this matter. Funding from the public sector, is contrastingly, more readily available, however, the applicant is inundated with a complex and rigorous application process which results in massive delays. This funding landscape has been further impacted by the COVID-19 pandemic and placed the public sector coffers under further strain.

In addition to the limited funding available for R&D funding, there is also a significant administrative burden that is also coupled to inefficiencies of government agencies and organisations (van Wyk, 2018). Furthermore, due to the limited number of multinationals or local biotechnology-based firms, there is a reliance on knowledge generation institutions such as universities. It has, however, been noted that South African academics choose the publication route due to incentives placed upon their institutions by government entities, such that there is a lack of appetite for patenting and subsequent commercialisation activities with includes license agreements and contracting (Cloete et al., 2006). IP contracts pose to introduce several bottlenecks and create negative perceptions at the expense of discovery and innovation outcomes. In the event of a truly novel technology being discovered, the correct stakeholder albeit private or public sector is unable to identify and fast track truly innovative products and technologies early enough such that they can be fast-tracked (Cloete et al., 2006). Localisation of technologies could be beneficial to South Africa, consequently, its government needs to take careful consideration and be cognisant of its challenges. It is imperative that a more crucial role is played by government, such that coordination within the system is achieved to ensure strategic alignment towards development (van Wyk, 2018)

The actors within the South African NSI may be capable of skipping stages of technology development and they may not follow the same path as developed countries, thereby they can “catch-up” with these countries (Lee, 2013). There has been significant evidence that the South African national system of innovation is able to develop both indigenous and international knowledge. However, the vast repository of information that is typically stored at universities, and is not actively translated into viable products, goods and services, due to several factors and institutional constraints (Uctu & Essop, 2012).

2.8. BIO-BASED TECHNOLOGY DEVELOPMENT AND POTENTIAL ON ECONOMIC DEVELOPMENT IN SOUTH AFRICA

Biotechnology is considered to be a new, knowledge-intensive sector, as economic activity and value is generated from knowledge creation (Cooke, 2002). Several emerging economies have emphasised the use of biotechnology to improve national innovation-based capabilities and the creation of a knowledge economy (Mroczkowski & Elms, 2009). South Africa, like the rest of the world, is striving towards a knowledge economy, however, the biotech sector is negligible, by international standards (Jordaan, 2016).

A bioeconomy is defined as a "knowledge-based production and use of biological resources in a biological process" which can sustainably provide goods and services across a wide range of economic sectors (Bracco et al., 2018; Dubois & Gomez San Juan, 2016). A bioeconomy usually involves three elements: "(1) the use of renewable biomass and efficient bioprocesses to achieve sustainable production; (2) the use of enabling and converging technologies, including biotechnology; (3) and integration across applications such as agriculture, health, and industry (Bracco et al., 2018)".

Cho, Hyun, and Lee (2007) assessed the Korean biotechnology sector and stated the knowledge transfer from public to the private sector as well as the support of private sector commercialisation of biotechnology were key in catching up to more advanced countries. Similarly, Cooke (2002) emphasised that to enable successful bio-based technology development, regional clusters were critical for the survival and ultimate success of these technologies. Particularly in India, the transition from chemistry-based to biology-based drug development has spurred the emergence of several new firms in the biotechnology arena (Chaturvedi, 2007). Typically, in East Asian economies, the focus is not on building individual firm-level capabilities, but rather on the building and developing of institutional mechanisms to support collective competence in the specialisation and configurations of available resources and knowledge (Mathews, 2003). Similar to the success of bio-based industry development in late-industrialising countries like Mexico, China, South Korea, Singapore, and India, South Africa also has the ability to achieve such successes (Chaturvedi, 2007; Cooke, 2002; Wong, 1999).

2.9 THEORETICAL FRAMEWORK

This study utilised three theoretical frameworks, (i) technological and economic catch-up (Lee, 2013); (ii) sectoral innovation systems (Malerba, 2005), and (iii) windows of opportunity (Soete, 1988).

2.10 CONCEPTUAL FRAMEWORK

This study was guided by the following conceptual framework presented in Figure 1.

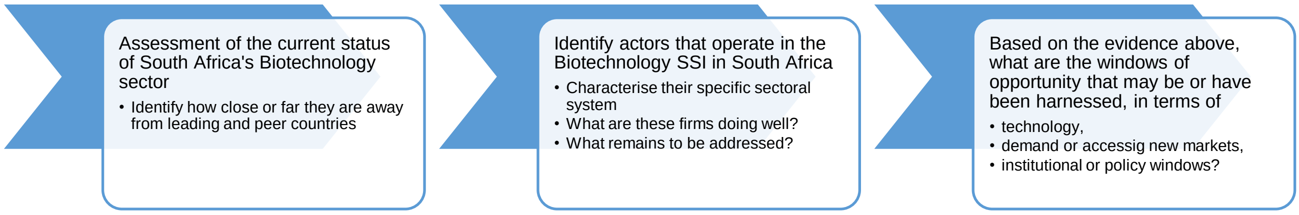

Figure 1. The envisaged conceptual framework identified for this research study.

2.11 SUMMARY

The intention for this literature review is to assess the advent of bio-based technology development as a key contributor to realise economic growth and catch up in South Africa by harnessing the identified windows of opportunity.

CHAPTER 3: RESEARCH STRATEGY AND METHODOLOGY

3.1 INTRODUCTION

The research model selected for this study used a mixed-method approach and followed a pragmatist's model to understand, infer and make recommendations relevant to the biotechnology-based sectoral system of innovation (SSI) in South Africa (Patel, 2015). Ivankova (2002), stated that the major tenet of the pragmatic approach is that quantitative and qualitative methods are compatible. Thus, the research problem can be better understood by analysing both numerical and text data which are collected either sequentially or concurrently.

3.2. RESEARCH STRATEGY AND DESIGN

This study used a sequential mixed-methods approach and entailed the collection, analysis, and integration of both qualitative and quantitative data obtained through the research study.

For the quantitative aspects, numerical data was obtained from analysing documents and publications. The data was used to conduct a comparative assessment of South Africa's biotechnology sector to both peer countries as well as countries that are leading the technology frontier. This analysis used descriptive statistics to provide a baseline of the status of the South African biotechnology sector innovation performance based on the selected indicators. For the qualitative aspect of the study, an analytical inductive approach was conducted by characterising the biotechnology-based sectoral system of innovation and assess possibilities for the country to catch-up, either technologically or economically, or both. In this manner, analysis was conducted to assess the various categories in the SSI framework with respect to the degree to which those categories might represent windows of opportunity for these firms and other entities. Using this approach, an assessment was made on why and under what circumstances these firms have achieved success or experienced failures (George & Bennett, 2005).

3.3. SELECTION OF PARTICIPANTS

For the quantitative component of the research study, a comparative assessment of literature-based sources, was made for South Africa, against peer and leading countries which included Mexico, India, the United States of America, Germany, and Singapore. For the qualitative aspects, participants were selected based on their direct involvement in the biotech-based SSI in South Africa. Additionally, public sector institutions as well as R&D organisations, and academic institutions were also involved in the study. The SSI of each specific participant was characterised and potential windows of opportunity that have been harnessed or could be harnessed were identified.

3.4 RESEARCH METHODOLOGY

This study used a mixed-method approach to sufficiently answer the research questions of the study. An analytical inductive, case study approach was used in an attempt to identify any key themes, and may also be assessed for the potential convergence (Tashakkori & Creswell, 2007). This approach has been defined by George and Bennett (2005) as scientific observations that are undertaken and selected data is used. This type of study has the ability to monitor and/or clarify aspects of a larger phenomenon, that is theoretically-based and not an amalgamation of all research findings. These findings may be used to test its operational ability against theoretical hypotheses.

3.4.1. Data collection:

Phase I – Quantitative approach:

The first, quantitative phase of the study included South Africa, Singapore, Mexico, India, the United States of America, and Germany, and included the assessment of six key factors. These factors include

(i) the number and nature of biotechnology companies that are registered in the country;
(ii) the value of government spending for biotechnology;
(iii) the value of venture capital;
(iv) industry funding for biotechnology;

(v) the number of researchers that currently work in this sector and

(vi) the turnover of the industry.

Other aspects included the assessment of the country's number of initial public offerings (IPOs), patents and publications, product pipeline, existing policies albeit for general R&D, biotech-specific R&D as well as commercialisation activities. Using the information obtained, data screening and analysis were conducted using descriptive statistics. The assessment of potential multi-collinearity of the datasets may also be undertaken, if any, as multivariate tests can be sensitive to extremely high correlations among predictor variables (Tabachnick & Fidell, 2013).

Phase II – Qualitative approach:

Data for the qualitative aspect was collected by performing semi-structured interviews, in the form of a questionnaire included in Appendix 1. Saunders, Lewis, and Thornhill (2009) stated that semi-structured interviews enable explanatory research, and open-ended questions presented in the questionnaire, provide avenues for generating a stimulating conversation, whereby, an in-depth discussion on the SSI of the respective actor was determined. The themes included policy landscape, technological capability, commercialisation activities and instruments, innovation networks and windows of opportunity. Once this system was characterised, the researcher has the flexibility to probe for more information on certain aspects and guide the actual conversation on potential windows of opportunity.

Data Collection and instrument

Interviews were conducted with the selected study participants (20 in total) guided by an open-ended questionnaire (Appendix 1). An information sheet was forwarded to potential participants detailing the nature of the study. Thereafter, each participant was contacted personally by the researcher and an appointment was made based on the participant's availability. Interviews were conducted using a suitable online platform once the participant had filled out the consent form.

If the participant was not comfortable with the research intent or had a level of discomfort pertaining to the research topic, then the interview was not held, and the participant was not obliged to participate further in the study. No remuneration was provided to the participants, to gain their approval to participate in this study.

If the participant did not grant permission to certain aspects stipulated in the consent form, then their wishes were respected during the undertaking of this study.

3.4.2. Primary data

Primary data was collected to address the research questions. Data selection of various indictors identified were captured using Microsoft Excel Spreadsheet as a database.

3.4.3. Secondary data

The study used data from other sources such as annual reports, industry reports, policy documents and academic journals to conduct the quantitative analysis.

3.5. DATA ANALYSIS

This type of mixed-methods study combines both aspects of quantitative and qualitative aspects to make it possible to obtain breadth and depth of understanding and possible corroboration of the findings (Kansteiner & König, 2020). By using the analytical inductive approach, data can be rigorously scrutinised to assess and identify potential themes, concepts, and models that may arise (Darabi & Clark, 2013).

3.5.1. Document analysis

Data was obtained by evaluating key documents to obtain information from peer reviewed sources pertaining to: the number and nature of biotechnology companies that are registered in the country; the value of government spending for biotechnology; the value of venture capital; industry funding for biotechnology; the number of researchers that currently work in this sector and the turnover of the industry. Also included in this study were the number of initial public offerings (IPOs), patents and publications, product pipeline, existing policies for general R&D, biotech-specific R&D as well as commercialisation activities. Data was analysed using descriptive statistics, and thereafter, was subjected to thematic analysis.

3.5.2. Analysis of Interview Data

Responses obtained from the semi-structured interviews were suitably examined and information was coded based on the content of responses received, and the themes of each aspect were reviewed. These results are compiled into a report of findings in Chapter 4.

3.6. LIMITATIONS OF THE STUDY

One limitation of this study may be selection bias. This may present a view of findings that are not representative of all biotechnology-based actors tested in this study. For some innovation indicators, data from a particular country was not available and therefore left blank.

3.7 ETHICAL CONSIDERATIONS

I affirm that this study was conducted by upholding the highest ethical standards and complied with the WBS research ethics policy. This study did not contain any ethical issues that involved human subjects, animals, genetic issues nor did it negatively affect the environment. Details pertaining to the consent of participants, handling of interviews, and the interview process have been outlined in section 3.4.1.

3.8 RELIABILITY AND TRIANGULATION

3.8.1. Triangulation

This study used a mixed-methods research approach, in order to conduct a better evaluation of the biotechnology-based SSI in South Africa. Triangulation arises from the ethical need to confirm the validity of the study process (Shoaib & Mujtaba, 2016). This approach used various sources of data, observers, methods, and theories to add depth to data collection and analysis while investigating a phenomenon (Ammenwerth, Iller, & Mansmann, 2003; Fusch, Fusch, & Ness, 2018). Consistency of data collection was imperative in this study.

3.8.2. Transferability

This type of research approach may be used to assess, evaluate and analyse other sectoral systems of innovation in South Africa.

CHAPTER 4: PRESENTATION OF FINDINGS AND DATA

4.1. INTRODUCTION

This chapter presents the findings of the current mixed methods study approach in accordance with the research questions stated in **Chapter 1.** The chapter is structured as follows: Section 4.2 presents findings from the quantitative aspects of the study and forms a comparative assessment of South Africa against other countries such as the USA, Germany, Singapore, India, and Mexico. Section 4.3 presents findings from the qualitative aspect of the study, which was informed by conducting semi-structured interviews with key stakeholders in the triple helix system of innovation in the biotechnology sector.

4.2. QUANTITATIVE RESEARCH FINDINGS

As South Africa is considered a late-industrialising country, its biotechnology sectoral system of innovation as compared to other leading and peer countries in terms of the six identified factors. These factors are prescribed in the Oslo Manual to enable comparative assessments using innovation-based statistics (OECD, 2018). The selection of countries included in the comparative assessment were selected based on the following criteria listed in Table 1.

Table 1. The rationale used for the identification and selection of comparative countries

No	Name	Reason for inclusion
1	United States of America	The frontier nation in terms of biotechnology-based innovation and technology development and is home to the highest number of biotechnology-based firms
2	Mexico	The leading Latin American country in terms of biotechnology-based innovation and technology development. Mexico was ranked 8th in terms of

		top biotech countries globally
3	India	The country is also a late-industrialising country and is currently among the top 12 destinations for biotechnology globally. It holds an approximately 3% share in the global biotechnology industry.
4	Germany	Is one of the top five countries in the biotechnology sector, and is probably the most lucrative destination for biotechnology in the European Union (EU)
5	Singapore	Is also a late-industrialising nation that has in place a dedicated economic catch-up strategy, and is also actively involved in biotechnology-based research, development, and innovation (RDI)

Based on the justification for inclusion provided in Table 1, a comparative assessment was made in terms of the number of active biotechnology-based firms operating in the six identified countries from 2009 to 2019 presented in Figure 2.

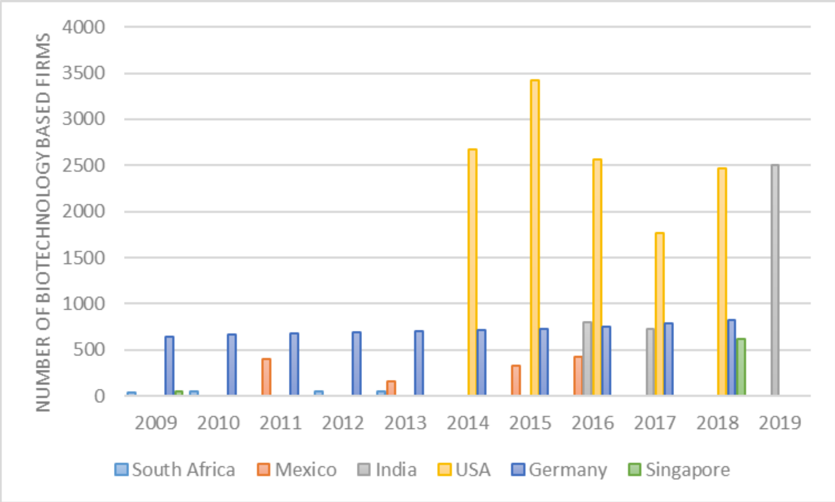

Figure 2. The number of biotechnology-based firms operating in the six identified countries. Source: https://stip.oecd.org/stat; www.ibef.org, https://www. Pharmbiosingapore.com/company, http://www.biotechnologyindia.company

In relative terms, the South African biotechnology industry accounted for the lowest number of active firms (~40 to 50) in comparison to the five other countries, with India and the USA having the highest number of operating biotechnology-based firms. Mexico was second-to-last in terms of the lowest number of firms, but this was approximately tenfold higher than South Africa. Germany had an average of 600 to 800 firms in years ranging from 2009 to 2018, with Singapore demonstrating an increase from 50 firms in 2009, to 620 in 2018.

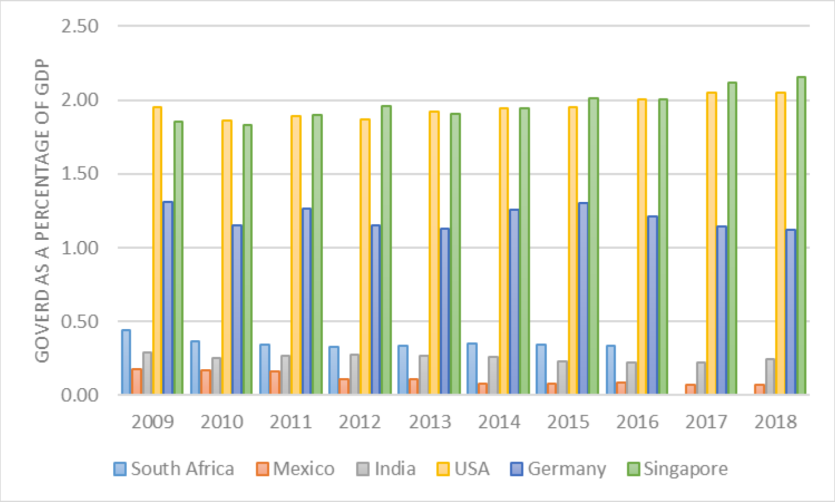

Figure 3. GOVERD allocation specific to biotechnology for the six identified countries. Source: https://stip.oecd.org/stat

In terms of government expenditure (GOVERD) specific to biotechnology as a percentage of GDP, the following summation was noted above in Figure 3. The South African government has since 2009, invested more funds towards biotechnology-based research in comparison to Mexico and India. The GOVERD of Germany averaged approximately 1.2 % of GDP for the ~ 10 year period, with the USA and Singapore demonstrating the highest contribution presented in Figure 3.

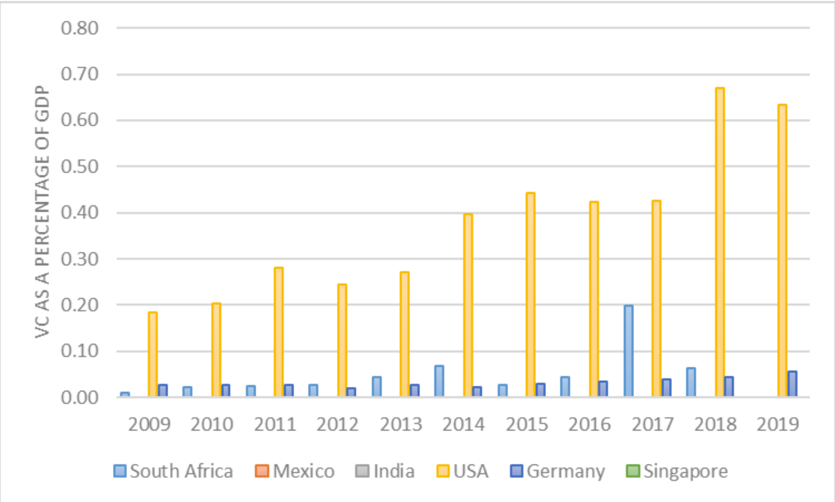

Figure 4. VC allocation as a percentage of GDP specific to biotechnology for the six identified countries. Source: https://stip.oecd.org/stat

Data pertaining to the amount of venture capital made available to the biotechnology sector was only available for three countries, South Africa, Germany, and the USA, as shown in Figure 4 above. Of the three countries, the USA demonstrated the highest relative contribution of VC funding, with Germany being the lowest. The South African VC trend increased by 0.19% between 2009 and 2017 shown in Figure 4 and thereafter dropped to 0.06% in 2018.

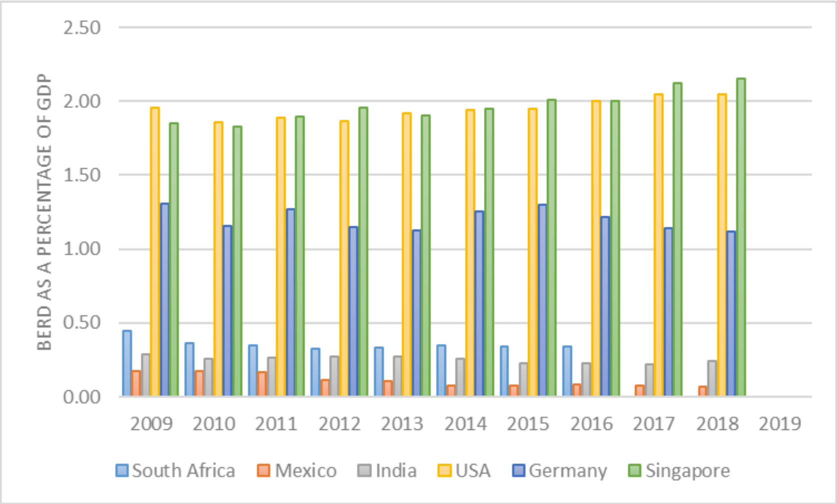

Figure 5. BERD allocation specific to biotechnology for the six identified countries. Source: https://stip.oecd.org/stat

Similar to the GOVERD trend presented in Figure 2, industry in the USA and Singapore demonstrated the highest contribution towards the biotechnology sector as a percentage of gross domestic profit (%GDP) shown in Figure 5 above. In contrasting, the industries of India and Mexico indicated the lowest contribution. Germany once against presented an equal contribution by industry to its government counterpart in terms of GOVERD versus BERD, with South African industry averaging ~0.36% of GDP.

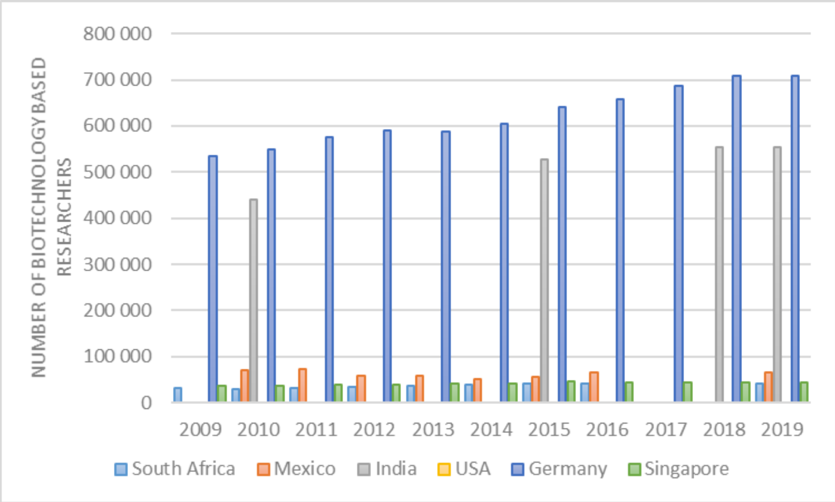

Figure 6. The total number of researchers involved in biotechnology-specific R&D within the six identified countries. Source: https://stip.oecd.org/stat

Regarding the number of researchers employed in each country on a full-time equivalence basis (FTE), Germany far exceeded the number of permanently researchers, with India demonstrating the second-highest performance. No data was available for the USA; however, it is expected to be one of the higher-performing countries in terms of this indicator. Singapore and South Africa both indicated the lowest numbers of researchers involved in R&D, 5th and 6th respectively, on a full-time basis, and this value was ~10 fold less than both India and Germany presented in Figure 6.

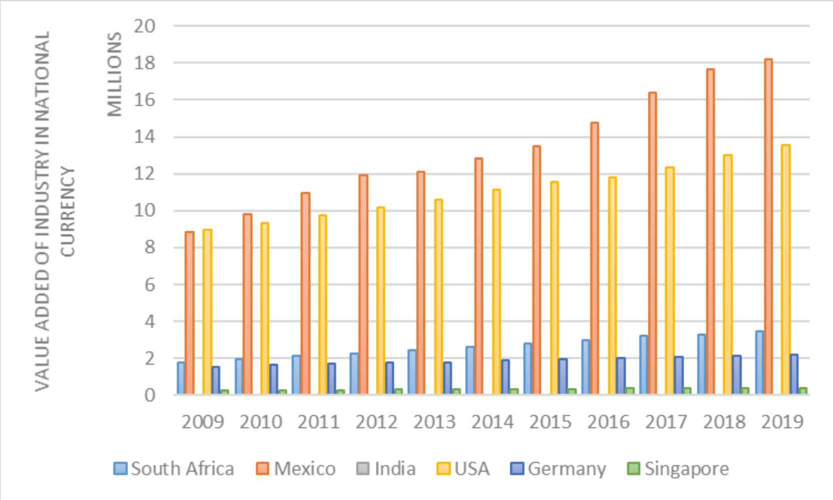

Figure 7. Value-added magnitude of the biotechnology industry in national currency, in millions for the six identified countries. Source: https://stip.oecd.org/stat

Based on value added by the biotechnology industry in the respective countries, measured by the country's national currency, the biotechnology industries of Mexico and the USA, demonstrated the highest contributions, in comparison to the other four countries assessed. The Singapore industry demonstrated the lowest performance, followed by Germany and South Africa. No data was made available to enable the assessment of the value contributed by the Indian biotechnology industry shown in Figure 7.

4.3 QUALITATIVE RESEARCH OUTCOMES

4.3.1. Study participants

A total of 20 participants were involved in this study shown in Figure 8. The interviews conducted were face-to-face using virtual meeting platforms and in a semi-structured manner. Respondents were allowed to respond based on their level of engagement and respective activities within the biotechnology-based SSI in South Africa. Before conducting the interviews, respondents confirmed their willingness to participate in recorded sessions. The allocation of the respondents according to their affiliation to a specific sector of the triple helix is presented in Figure 8.

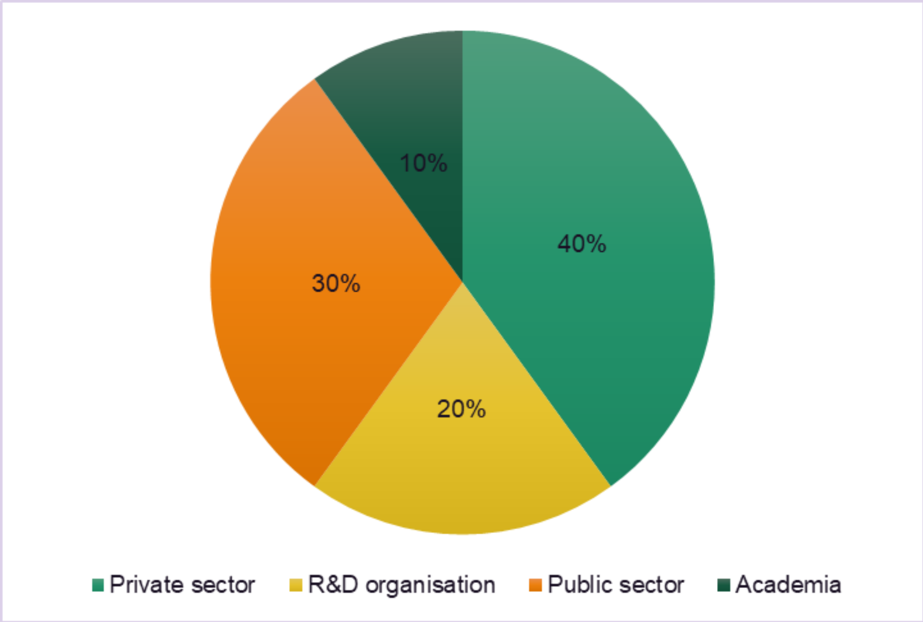

Figure 8. Distribution of study participants

4.3.2. Comparative assessment of peer and frontier nations

In the first instance, the baseline performance of the South African biotechnology industry was compared to the USA, India, Mexico, Germany, and Singapore, and ascertained using quantitative methods. Additional factors such as the country's IPOs, patents and publication output, product pipeline, policy landscape for both general and biotech-specific R&D and commercialisation activities were then assessed using both quantitative and qualitative approaches.

The first innovation output evaluated in the South African biotechnology SSI, was that of initial public offerings (IPO). Based on an intensive assessment of the IPO landscape, South Africa has not had any biotechnology-based firms that have embarked on an initial public offering (IPO) since 2005 (Semete-Makokotlela, 2015). In terms of patents and publication outputs the following data was obtained and presented in Figures 9 and 10 below. South Africa has averaged ~15 patents per year for the nine-year period, with the highest output of ~23 patents made in 2014. In comparison, the USA and Germany averaged approximately 4800 and 633 patents per annum respectively in the same period, 2009 to 2017 (OECD, 2020).

Figure 9. The number of biotechnology-specific patents filed from 2009 to 2017.

In terms of publications, the number of publications, has demonstrated a steady increase, and is presented in Figure 10. As of 2018, the country produced ~ 25,000 publications in a year. However, with an average of ~18,650 publications per annum in the 10 year period, this number was only ~3% of the number of publications produced by the USA in the same period.

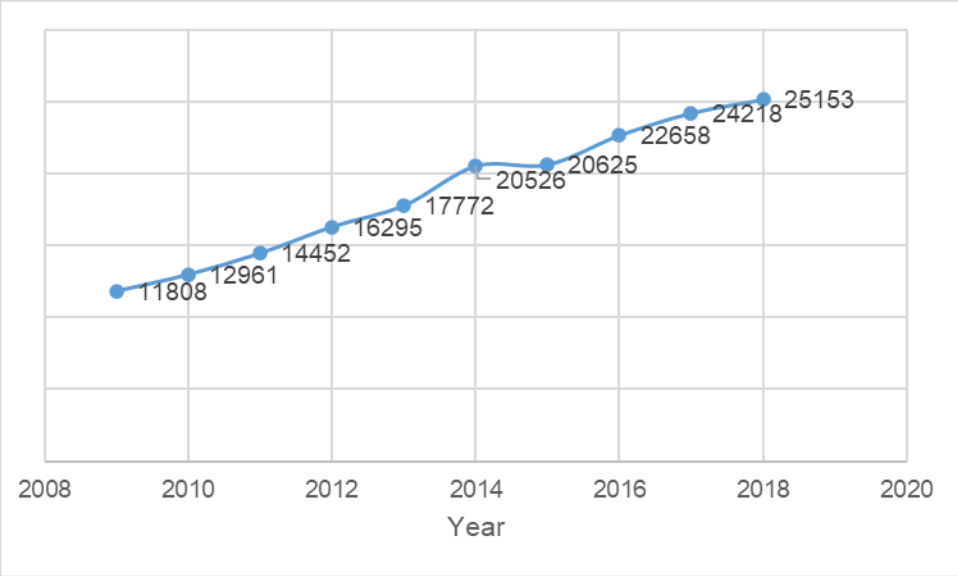

Figure 10. The number of biotechnology-specific publications accepted in peer-reviewed journals from 2009 to 2018.

Other than assessing the overall performance of the country in terms of publications and patents obtained from the OECD database, the contribution of the respective stakeholders regarding these innovation-based outputs, within the biotechnology SSI in South Africa were also assessed and listed in Table 2.

In terms of publications, patents, and products, all study participants claimed to generate ~ 30 publications per year in total. A majority of these outputs come from academic institutions like universities and universities of technology presented in Table 2. Patents are very limited, with only one local academic institution reporting that it generates at least one patent per year. The other patent mentioned in Table 2 was that of a provisional patent application made by a local SMME 003. Regarding products, a total of 279 have been developed by the 20 respondents that provided inputs into the study.

Table 2. List of interview respondents and their overall outputs to date, in terms of publications, patents, and products

Participant number	Stakeholder category	Designated code	No of publications	No of patents	No of products
1	SMME	SMME001	0	0	2
2	SMME	SMME002	0	0	125
3	SMME	SMME003	1	1	4
4	SMME	SMME004	0	0	0
5	SMME	SMME005	0	0	5
6	SMME	SMME006	0	0	8
7	SMME	SMME007	3	0	9
8	Academia	AC001	8	0	0
9	Academia	AC002	12	1	0
10	Government	GOV001	0	0	0
11	Government	GOV002	0	0	0
12	Government	GOV003	0	0	0
13	Government	GOV004	0	0	5
14	Government	GOV005	0	0	0
15	Government	GOV006	0	0	0
16	R&D organisation	RND001	3	0	8
17	R&D organisation	RND002	3	0	8
18	R&D organisation	RND003	0	0	105
19	R&D organisation	RND004	0	0	0

20	Venture Capital	VC001	**0**	**0**	**0**
	Total		**30**	**2**	**279**

4.3.3. Biotechnology-based policy

Policy, specifically those that are biotechnology-related, also has an impact on the operation of this particular SSI. Policies that have either enabled or impeded the efforts of the stakeholders within the biotechnology-based SSI are listed in Table 3.

Table 3. Classification of biotechnology-related and non-biotechnology related policies that impact the sectoral system of innovation in South Africa

	Name of policy	Year	Theme	Owner	Impact	Reason
1	Bioeconomy Strategy	2013	Biotech related	Department of Science and Innovation	Enabling	Directs and informs R&D
2	Act 36 registration of biological products	1947	Biotech related	Department of Agriculture, Rural Development and Land Reform	Impeding	Excessive time period required to register products before they can be sold commercially. Act requires some revision to create a more enabling environment
3	SAHPRA regulatory framework	n/a	Biotech related	Department of Health	Impeding	Excessive time period required to register products before they can be sold commercially. Policy requires some revision to create a more enabling environment
						Certain SAHPRA regulations are killing the industry as there is too much red tape and too many regulatory hurdles. Does not create an enabling environment and

						makes South Africa a difficult destination to trade in.
					Enabling	Provides legitimacy of product compliance and demonstrates that products are safe for use
4	Local SMME support and development	2020	Non-biotech related	Department of Small Business Development	Enabling	Provides details and nature of support available to small businesses. Provides assistance to previously disadvantaged SMMEs
5	COVID economic recovery plan	2020	Non-biotech related	South African Government	Enabling	Government has identified the biotechnology SSI as a key area to boost economic growth and development post-COVID
6	Circular economy development	2017	Biotech related	Department of Environmental Affairs	Enabling	The country is committed to sustainable development to balance waste usage and attaining broader economic impact, thereby creating a large opportunity for biotechnology-based companies

7	Preferential Procurement Policy Framework Act 5 (PPPFMA)	2000	Non-biotech related	South African Government	Enabling	The amendment of the core PPPFMA policy was done to enable swifter payments to be made to SMMEs to contribute to their liquidity.
					Impeding	There are restrictions in terms of importing equipment which causes significant delays. Causes organisations to lose agility when trying to pass clean audits in terms of procurement
8	Indigenous knowledge benefit-sharing	2004	Biotech related	Department of Trade Industry and Competition	Enabling	These policies have been enabling in terms of developing new products using local knowledge and biodiversity. Traditional knowledge holders receive remuneration for their inputs into product development
9	Biorefinery development	2013	Biotech related	Department of Science and Innovation	Enabling	This is an aspect covered in the Bioeconomy policy. Aims to develop integrated bio-refinery concepts for the co-production of food and non-food based

						products, thereby creating opportunities for biotechnology-based SMMEs
10	Industrial Policy Action Plan (IPAP)	2007	Non-biotech related	Department of Trade Industry and Competition	Enabling	Has outlined and implemented various instruments such as the Support Programme for Industrial Innovation (SPII) and other funding instruments.
11	Agricultural policy action plan (APAP)	2015	Biotech related	Department of Science and Innovation	Enabling	Aims to translate the challenges outlined in the Integrated Growth and Development Policy for Agriculture, Forestry, and Fisheries into concrete steps which may create several opportunities for biotechnology-based SMMEs
12	Inter government collaboration framework	2005	Non-biotech related	Several ministries and other government entities	Enabling	This collaborative framework enables entities within the NSI as well as other spheres of government, such that support is available.
13	Intellectual	2008	Biotech	Department of Trade Industry and	Enabling	This act was created such that IP outcomes from publicly financed R&D

	Property Rights Act (IPR- PFRD)		related	Competition		which have the potential to create social and/or economic value are protected and commercialised for the benefit of the people of South Africa. National Intellectual Property Management Office (NIPMO) has become more responsive, however further work is required
					Impeding	Can be restrictive and is counteractive in terms of promoting collaboration. The problem statement contained in the IPR act of 2008 needs rectification to be more enabling
14	Companies and Intellectual Properties Commission (CIPC)	2008	Non-biotech related	Department of Trade Industry and Competition	Enabling	Formed as part of the Companies Act, and hasa special mechanism in place to assist small business with the lodging of patents, company registrations, etc.

15	Use of genetically modified organisms	1997	Biotech related	Department of Science and Innovation	Enabling	Legislation for the use of GMOs in South Africa has been passed. This gives us a competitive advantage over countries like Australia
					Impeding	Some provincial governments restrict the use of GMOs even though national policies condone their use. A typical example of policy incompatibility
16	Use of bioplastics	n/a	Non-biotech related	To be determined	Impeding	Lack of regulatory environment leads to a lost opportunity
17	Treasury Central Supplier Database (CSD)	2004	Non-biotech related	National Treasury	Impeding	Some small business cannot register on CSD and there aren't any enabling mechanisms to enable them to become service providers to the state
18	Waste management regulations	2008	Non-biotech related	Department of Environmental Affairs	Impeding	Due to the lack of policy regarding waste, waste removal, sorting of waste prior to disposal, and disposal to landfill, there is a lost opportunity for mechanisms to drive a circular economy

19	Reserve bank policies	n/a	Non-biotech related	National treasury	Impeding	Certain policies pertaining to exchanges are limiting to the business prospects of the country
20	Development funding initiatives (DFI)	2010	Non-biotech related	Department of Trade Industry and Competition	Impeding	Funds take too long to administer
21	National Biodiversity Act	2004	Biotech related	Department of Environmental Affairs	Enabling	More streamlined processes have been noted since the inception of this act.
22	Cell therapy-specific policies	n/a	Biotech related	To be determined	Impeding	There is a lack of policy in the medical biotechnology sector, specific to the use of precision cell therapy, this hinders/restricts this form of healthcare to be accessed by those that need it. In the EU there is a good policy framework for cell therapy. From the design of the trial, performing necessary regulatory checks In South Africa, the Department of health lacks the will and appetite for such a cutting edge form of treatment

Based on the engagements with the various stakeholders within the biotechnology SSI, it was deduced that the general innovation policy landscape in South Africa, whether biotechnology-based or non-biotechnology-related, is indeed interesting. There is a complex matrix consisting of several policies within the South African context, but there is significant miscommunication and misalignment. For instance, the IP generated using public funds, does not belong to the state, despite the IPR Act being in place. Foreign entities may be able to procure this locally developed IP and take it out of the country for a financial gain elsewhere. The state therefore cannot claim any ownership or try to attain any value generated from this locally developed IP.

South Africa has world-class policies, however, it is more the implementation and authenticity thereof that is lacking. Prior to even being gazette, policy drafting is said to be a slow and drawn-out process, that lacks an element of practicality. Participant GOV002, a government entity, aptly stated that ***"policies need to be adapted prior to being adopted"*** by the country. Furthermore, it has been alluded to that not enough time is spent on gathering and analysing data before policies are drafted. Similarly, policies that may be beneficial in the long term are not given sufficient time to reach the required maturity levels and then they are revised or made obsolete. This hastiness for change does not let the full horizon of the policy be reached. There is also a lack of tools that are required to support this environment, for example, policies pertaining to conventional lending for biotechnology firms are lacking as current models cannot be used to fund initiatives despite how lucrative the opportunity may be. Lack of policy in this sector further exacerbates the requirement for using public sector funds as a co-fund component, to access funding reserves. In some instances, regional policies are excellent, such as ones specific to the Eastern Cape, Limpopo, and Kwa-Zulu Natal provinces, but the implementation of these policies is lacking. Such policies may therefore need to be overhauled or retrofitted to attain more functionality in the current biotechnology landscape.

Within the NSI there is a significant aspect of coordination that is required in terms of managing R&D funding initiatives. A common scenario in the South African biotechnology SSI, is that a viable idea or proof of concept is successfully developed to a suitable technology maturity level with the required level of financial support. However, when commercialisation initiatives are set in motion, the policy required is not in place, or policy frameworks are not synergistic or enabling and as a result, the technology is not commercialised/implemented and then becomes uncompetitive or obsolete.

In terms of adhering to all regulatory frameworks stipulated from the different policies, it has been stated that due to the unconducive policy landscape, it is more difficult to conduct business activity in South Africa. This is in comparison to the USA even though the FDA is said to be so stringent. Perspectives obtained from the SMME-based participants, on this matter, indicate that the country needs to be more agile in terms of approving products that already have FDA and even EFSA accreditation. In that, the regulatory bodies in more developed nations would have conducted extensive analysis prior to approving these biotechnology-based technologies and products. As an example, in South Africa, we require Act 36 registration for biological products, as well as SAHPRA approvals for biopharmaceutical molecules. However, if FDA approval has already approved these products, then South African accreditation and approval should materialize by default, and the process need not be replicated for the sake of it. Several stakeholders have inferred that SAHPRA requires additional management in order to overhaul their operations such that they increase the rate of product acceptance. In the USA, it could take six weeks to get market products to the market, whereas in SA, it could take approximately seven years. Significant assistance is required to increase the responsiveness of the SA health industry.

Implementation of policy and organisational ability is more important to truly support the sector and realise reward/benefit/impact. If a policy is implemented, it will be the game changer for the country, as South Africa has the potential to flourish and leapfrog the EU, UK, and USA, as Africa presents with a wealth of case studies. For local biotechnology-based companies, the availability of specific policies is said to have a beneficial impact but does not necessarily impact business activity as product uptake in the market is generally unaffected as international guidelines are being adhered to. However, these types of policies could drive the use of local products as import replacements.

Policies that highlight the key focal areas of the economy must be drafted such that priority areas are known. At present, there is a lack of focus and cohesiveness. A further limitation in the policy environment in South Africa is the absence of an implementation body, which ideally ought to be the Technology Innovation Agency (TIA). Specific policies can be of value must be drafted in order to coerce academics to move out the mindset of only publications and student graduations as an output, and actively pursue commercialisation activities. These initiatives must be suitably incentivised such that they may create a dedicated effort by players in the field. Legislation must however be strong in order to promote these activities.

It is important that when a policy is drafted, it is done in a bottom-up fashion, otherwise, there is a risk that the envisaged policy will be out of touch and far from the reality of its intended environment. There could be benefits realised from generating more localised policies that could improve the countries current efforts/status. As a country, South Africa must be able to adapt policies that are adopted from other environments, as a country it is guilty of deploying “adopting without adapting” instruments.

South Africa has made big strides in providing mechanisms such as enabling policies, however, guidelines for the strategy and framework for implementation must be drafted such that they are streamlined to the available support. For example, the CIPC-based policies could be initiated such that South Africa becomes an examining country in terms of patents, this would thereby protect the country from patent infringements. Furthermore, policies surrounding trade tariffs also need to be revised such that the competitiveness of the South African industries is maintained and endorsed. Other reserve bank policies also need to be modified so that a more synergistic business environment is created. The country needs to execute against policies that are in place, examples include the use of GMOs. This will streamline efforts to maximise opportunities. Unfortunately, it must also be mentioned that the country is so flawed with corruption that policy regardless of how good, does not bring about the required impact.

4.3.4. Technological capability assessment

South Africa is said to be an innovative nation, with a healthy appetite for entrepreneurship. It is said that the country leads the African continent as it has well-established R&D and academic institutions and training systems are in place. Based on the perspectives obtained from the study participants, South Africa is said to be on par with peer countries and are some instances very competitive in relation to the rest of the world. In other areas, such as pharmaceuticals and bio-production of pharmaceuticals, the country is seriously behind the global leaders, in terms of capabilities and infrastructure.

In comparison to the rest of Africa, South Africa is at the forefront of bio-based technology development and has to date produced more innovation-based outputs. In terms of technological development, South Africa is listed as one of the top five contributing countries on the continent. Once the technology is ready to go to market, is when the country is not well equipped to survive the valley of death. There is a lack of awareness of how to make these technologies a success.

South Africa has a good life science sector which has shown an increase in R&D outputs, and in the past 10 -15 years, the cost to do biotechnology-based research has significantly decreased. The country has developed a better global standing in terms of medical devices and medical biotechnology innovations, however, it still relies significantly on external competencies and not doesn't make a concerted effort in being self-sufficient. Also, there is a sense of hastiness and lack of patience in riding out the technology development such that it reaches maturity, and benefits may then be realised.

In Africa, Egypt and Morocco are leading in terms of aquaculture and agriculture technology development, and are currently the largest producers of fish on the continent. Tunisia is also said to be increasing its efforts in building a bioeconomy. Rwanda, Nigeria, and Ethiopia are fast becoming the destination of choice for large multinational companies to invest and develop technologies in these countries. In terms of community skills and digital environment, the country has been surpassed by some other African countries. These developments are not necessarily high-tech, but users in these countries have access to technology that suits their needs.

In comparison to its BRICS counterparts such as India, Russia, and China, the country is behind in the e-health, medical, and agriculture-based technology development. Brazil too has been said to have made a concerted effort over the past 10 years, and the drive was said to be stimulated by a joint effort of both public and private sector initiatives.

The country has well-entrenched activities in the food-based industries such as Illovo, South African Breweries (SAB), NCP Chlorchem, and BASF. Most of these industries use fermentation technology, which is generally considered old technology, and there is certainly a gap or shortage of newer, high-value biotechnology initiatives. In terms of biomanufacturing competencies, South Africa is behind the rest of the world, as contract manufacturing facilities are limited. The country is good, however, at localising foreign developed technology and executing aspects of secondary innovation to adapt the product or technology to the local climate. South Africa needs to go back to basics and look internally and take advantage of the local landscape. The country has several verticals of excellence, albeit narrow, however, has a more generalised and limited mindset in terms of translational research. The country requires commercialisation strategies to deliver technologies from the laboratories to the market, and attention must be placed on conducting techno-economic assessments especially in terms of local manufacture and supply of locally developed products. Another important consideration for local product development is to ensure that international verification is obtained in order to support and validate the local technology.

Sometimes R&D developed in the country does not bear relevance to the rest of the world, yet the country still imports a large degree of technology. At present, the country is at least 10 years behind the global leaders. Locally developed IP is still lacking, yet South Africa has had a long-term history with R&D in infectious diseases and has one of the best HIV research centres in the world (Thorsteinsdóttir et al., 2004). In the instance of not having a response to the COVID-19 pandemic, this is an indication of a defunct RDI system, which is limited and requires improvement (Onyango and Ondiek, 2022).. South Africa has the potential to be global leaders, however, still needs more enabling infrastructure and entrepreneurship needs to be stimulated (Patra and Muchie, 2017).

Previously, the local biotechnology sector of South Africa consisted mainly of large pharma-type companies. SMMEs are said to struggle in SA and they rarely break even (Semete-Makokotlela, 2015). South Africa also has an SMME development fund, as it has been identified that there aren't enough small businesses in the system. This instrument was therefore created to improve this situation. At present, there is ~ 20 startups in the agricultural biotechnology sector (Uctu & Essop, 2012).

South Africa has good universities and produces a good caliber of students and skilled scientists, even though it does not have world-leading universities. Based on the R&D survey conducted by African Union, the country has good scientists and is on par in terms of global position in terms of R&D investments, student output and caliber as well as infrastructure (AUDA-NEPAD, 2019). This caliber of scientific outputs can develop cutting-edge science, an example of which includes Kwazulu-Natal Research Innovation and Sequencing Platform (KRISP) hosted at UKZN, which has attracted global attention. It must be however mentioned that previously disadvantaged universities are still a bit lacking.

The current talent pool for RDI in the country is abundant, with lots of expertise and ambition, however, this is not translated into impact and outputs, as the academic concepts rarely mature out of the university environment. The coupling of good skills for science to the technical aspects required for translational technology development is lacking, and this skillset is also siloed. It has also been said that the correctly skilled people are not involved in the development of bio-based innovations and the scale up thereof. There are gaps in the skill set, as well as in the technology value chain, as there is a distinct shortage of downstream processing skills. This creates the opportunity to train more artisans and technicians instead of core science skills which may address this skill shortage. It also said that due to the decline in the education system of South Africa, the abundance of well-trained personnel is dwindling.

Stakeholders within the South African biotechnology-based SSI are keen, engaged, and have a willingness to develop high-tech technologies, however, there is a low appetite for risk and particularly in biotechnology-based entrepreneurship. The biotechnology SSI in South Africa has several enabling mechanisms in place, however, challenges still exist. The NSI and its operation do not encourage collaborative activities, and incentive levels need to be changed at a regulatory level. The Technology Innovation Agency (TIA) has demonstrated its support for local technology development, and there are a few instances of success. The country tends to compare with other countries that are out of its league. For example, in terms of technology or innovation hubs. However, internationally, some technology hubs are vast and exist across entire cities.

In terms of investment and funding availability, South Africa tops the list in terms of the amount of resources invested in STI-based activities on the African continent. There are a few other countries in Africa that have such a balanced portfolio in terms of public and private contribution to R&D. The National Research Foundation (NRF) does well to support early-stage research, however, there is limited funding available for translating research to the market, and despite the significant investment has been made in the country, the outputs are not realised. Funding instruments lack coordination and influence and almost encourages the siloed nature and direction of the R&D. Due to this silo-ed nature of the NSI, there seems to be a perception of a limited pipeline of technologies. If a more collaborative network of stakeholders is stimulated, it may create a more sustainable pipeline of technologies or awareness thereof, and this may promote more successes. Funding mechanisms that are presently available in the country drives the behavior and needs significant change in order to drive cohesion. At present, there is no guiding force to ensure that stakeholders are obligated to work together. This could be facilitated by having appropriate and enabling policies in place.

Due to the length of development ~ 5 to 8 years required for biotechnology-based technology development, there is not enough funding available to last that period of time. There is also a lack of venture capital funders in the country, and this segment of funding was barely non-existent prior to the arrival of OneBio. Databases or repositories of stakeholders, such as the Innovation Bridge initiative, are required in order to find collaborative partners within the SSI to drive impact and also to secure funding for the entire duration of technology development. Central platforms such as these are relatively under-utilised despite their good intentions as there is no requirement for the relevant actors to work together.

In terms of organisational capability on a global standing, South Africa does not present with a concerted and synergistic effort amongst the key actors, and its initiatives are disjointed. In comparative terms, the country is relatively small and faces several systemic issues such as limited support and access to infrastructure, however, pockets of excellence do exist. Several programmes are in operation which enables the country to develop technologies from proof of concept to commercialisation. However, the country is said to lack agility, and despite there being these enabling mechanisms in place to develop R&D across the technology readiness levels (TRL).

In terms of infrastructure, there is a stark disparity in terms of research enabling infrastructure present in the country, in comparison to the rest of Africa. Outside Africa, the country fares mediocrely in terms of infrastructure, even though it has the best infrastructure in the SADC region. It must also be noted that, despite being present, infrastructure is aging and there are a few white elephants. There is also a perception that there has been a lack of investment for enabling infrastructure, however, entities such as TIA has made a significant investment in this regard. In terms of infrastructure access, the government needs to improve access to state-owned facilities such as those commissioned at TIA and CSIR, as well as, university infrastructure that is available at some universities. It has been noted that the CSIR's BIDC has a unique offering in being able to scale up processes. An infrastructure database may also be useful, to see what type of infrastructure is available for use, as currently there seems to be limited pilot and commercial-scale infrastructure as well as a general shortage of suitable downstream processing equipment. This will create an opportunity to construct regional clusters such that the associated skills and infrastructure is based at a known location.

In terms of the rest of the world, South Africa's response, or rather lack thereof- to the COVID-19 was a clear indication of the state of affairs. A year into the pandemic, and there was no participation by the country in the vaccine agenda, and no stimulus or directive from the government to drive or encourage this agenda. On the other hand, governments like South Korea drafted legislation to ensure that local entities get the required support in order to fight the disease.

The country is said to have a high degree of opportunities, as the current social state and levels of inequality drives impact for development. There is also high availability of labour and raw materials. South Africa should be gearing up to address local challenges using local expertise and conditions, however, due to bureaucracy, corruption, less competent leadership, this opportunity is under-utilised. Entrepreneurs face a difficult time in the country, and in some instances have to make several different attempts at starting biotechnology-based enterprises. There is also little hope for the country in terms of developing a more established and cohesive economy, which bridges aspects of both the formal and informal sectors. At present, the country is lagging too far behind the rest of the world, and no incentives are in place to drive the change of behavior that is required. The country should use the expertise available to be world leaders, and not always resort to being followers. Non-governmental agencies (NGOs) are more operational and make bigger contributions in smaller African countries in comparison to South Africa.

4.3.5. Commercialisation activities and instruments used by the various actors

In terms of commercialisation, the study participants were asked to categorise publications, patents, products, or company IPO in terms of importance to their organisations.

Many actors in the biotechnology-based SSI stated that products were the main mechanism of commercialising their technology development. Based on their experience, products are key drivers for commercialisation, as they demonstrate scalability, market feedback, and technical performance. However, several SMMEs further stated that the product itself is not the main aspect of commercialisation, as products need to be coupled with brand awareness and service offering to their end-users.

Having patents is also beneficial for some actors within the SSI as they demonstrate the types of technologies that may be available for license and are important as some people look for licensable technologies. Furthermore, it also indicates the collaboration network of the technology and the organisation.

Publications are said to be more of an academic output and do not have a significant bearing on commercialisation. Of the 20 study participants, there were no firms that were involved in biotechnology-based firm IPOs in the country to date. The general feel of the biotechnology-based SSI is that commercialisation activities are weak and that the country does not license technologies well. The mechanisms of commercialisation differ for various actors with the triple helix.

4.3.5.1. Government/public sector

Typically government ministries do not commercialise technologies based on governance models. However, some public sector stakeholders require a commercialisation output, such as a technology license in lieu of the investment made. However, it has been recommended that government should rather place emphasis on building a pool of tech-savvy entrepreneurs to both develop as well as license out technologies for the country.

Furthermore, there needs to be a higher conversion rate of invention/technology disclosures to patents in the sector, which may thereby create sustainable pipelines for the individual biotechnology-based businesses. This may also contribute to the profitability of the business after capital is invested, such that a return on investment may be generated. At present, public sector funders generally provide follow-on funding to the business, which creates an unsustainable environment. Public sector funders should work with entities such as the SA SME fund and OneBio to conduct business development initiatives. This is to ensure that the team associated with the technology development is equipped to address both the business and commercialisation activities and the core science elements. If this is the instance pursued by the public sector funding agency, there are clauses for royalties depended on the type of technology and the market it is destined for. Another mechanism that is sometimes used entails equity stake models based on quasi-estimates for a respective technology.

4.3.5.2. Private sector

In this sector, actors enter technology license agreements and distribution deals with their partners, and once the technology is developed, royalty agreements are put in place. The royalty structure is negotiated based on the type of technology and products and could range from 1 – 25%; depending on the type of product and the pricing model used.

In most dynamic interactions, joint technology development occurs with partners, and incentives and reward upon commercialisation are split accordingly, as a result, the risk is also shared. This results in a joint prosperity agreement principally because the South African biotechnology landscape is relatively thin, and is best to create opportunities by sharing and forming collaborative platforms such that each entity can contribute to and has a vested interest in the success of the technology. At present, South Africa biotechnology-based SMMEs operate on a business to business model (B2B) regarding the manufacture and sale of products. This creates co-dependencies, ecosystem building, business sense, trust, partnerships, and two-way supply to customers.

Local private sector partners have noted a trend, wherein technologies are in-licensed and then localised. These firms conduct R&D and technology development concurrently, to maintain their competitive advantage. Additionally, the cost of patenting is high, and therefore, technology is generally maintained as know-how or trade secret. Sometimes businesses are encouraged to patent as a mechanism to protect the investment.

4.3.5.3. R&D organisations

These entities seem to have a more streamlined approach to commercialising technology as they have in place a dedicated team of business development and commercialisation managers. As the technology of interest is usually developed in collaboration with a market partner, this almost provides a guarantee that when the technology has matured to the required readiness level, it can be suitably commercialised and taken up by the market. Depending on the type of technology, commercial partners may negotiate the terms of the license on either an exclusive or non-exclusive basis, as well as the license period and royalty share. There is no blanket approached that is used in these interactions, and all terms are discussed and negotiated upon. In the instance of R&D centres that provide support to SMMEs, royalty terms only take effect once the business attains sustainability, however, these payments do not exceed the value of the initial investment.

These R&D institutions are also looking at other avenues for commercialisation, such as obtaining an equity stake in the company or creating more enterprise-based solutions whereby, the private sector entity can access skill/services/products offered by the R&D organisations as a sole service provider.

4.3.5.4. Universities

According to the academia-based researchers who partook in the study, commercialisation activities at South African universities are quite nominal. In the instance where technology of value is developed, the university makes use of the technology transfer office, and the model used for spin-out or technology out-licensing is dependent on the type of technology. No further engagements were made with the technology transfer offices of these institutions to substantiate these claims.

4.3.6. Nature of relations

Study participants were requested to outline their specific innovation networks and describe the nature of the interactions, in terms of listing their existing collaboration partners and suppliers. Furthermore, the nature of these relationships needed to be highlighted in terms of them being either static or dynamic. These individual networks were consolidated to portray the existing biotechnology-based SSI network of the 20 participants and are presented in Figure 11 below.

Based on the interactions, it may be ascertained that government entities, represented in green, such as ministries, agencies, funding bodies, and research organisations form the crux of the biotechnology-based SSI in South Africa as shown in Figure 11 below. Academic institutions, including almost all of the local accredited universities and TVET colleges, were named as network partners by the study participants. A negative finding was that none of the local academic study participants listed other fellow local universities as their network partner, however, and instead mentioned international higher education institutions within their networks. Industry partners, denoted in red, form the outer layer of the biotechnology-based SSI network. This finding illustrates the fairly static nature of interactions between industry partners and government and academic institutions.

The size of the nodes depicts the number of instances where a particular technology partner was mentioned by a respective study participant. From this study, TIA was identified as the most commonly mentioned technology partner, stating the relevance of such an entity of the South African biotech-based SSI, followed by the DSI and the CSIR.

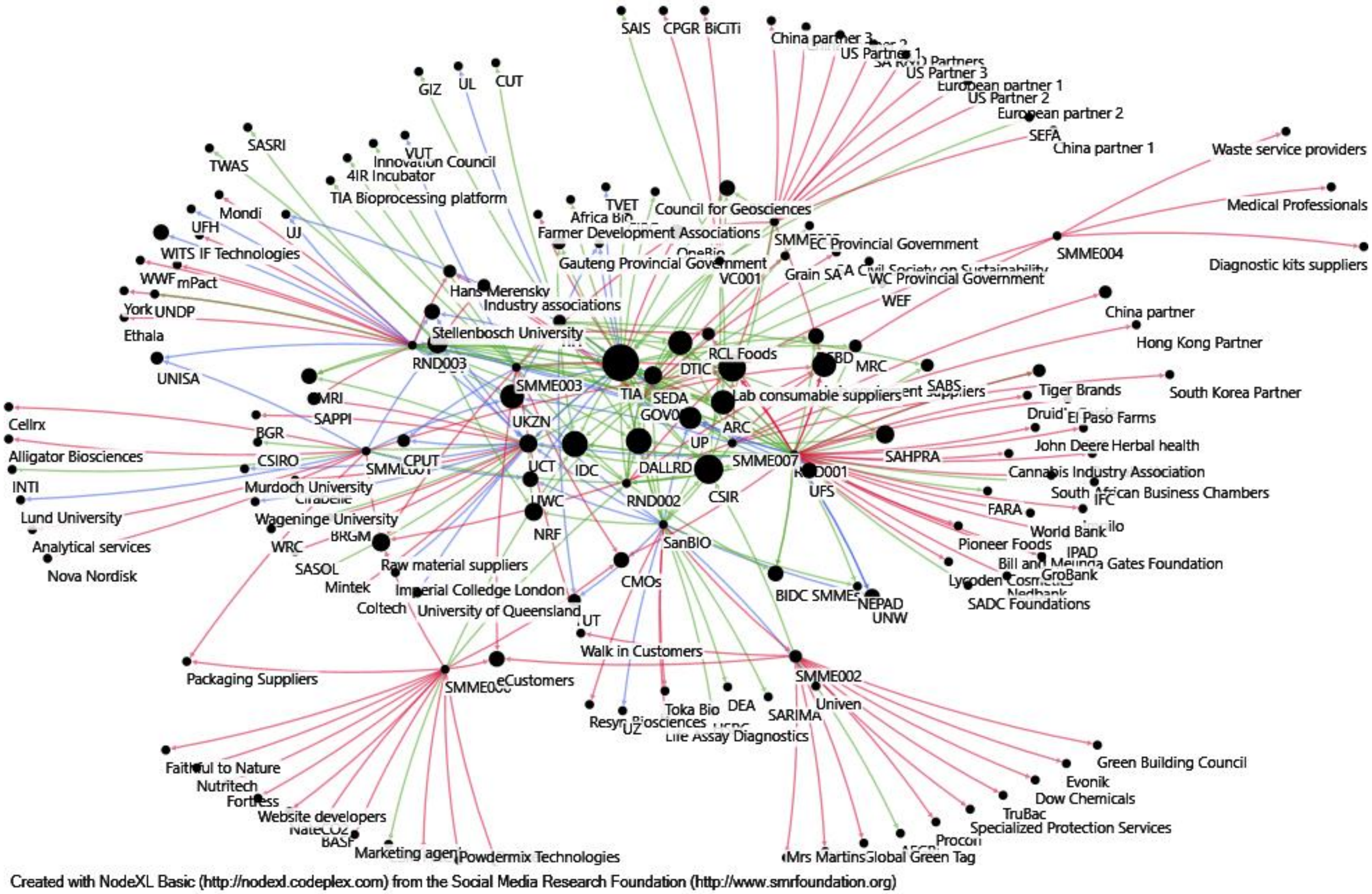

Figure 11. A combined representation of the biotechnology-based SSI for the participants in South Africa

4.3.7. Windows of opportunity

Windows of opportunity were identified by the study participants in terms of (i) scientific novelty, (ii) finding and accessing new markets and market demands, and (iii) new policy interventions.

4.3.7.1. Scientific novelty

Circular economy development is a major opportunity for the country. The diversification of existing established industries such as the pulp, paper, and sugar industries is required and may create new avenues for application. This includes the production of traditional chemicals using bio-based processes and focuses predominantly on the beneficiation of waste into high-value products. South Africa currently holds 30% of the global market of dissolving wood pulp and can take advantage of that position and become world leaders.

South Africa has a wealth of opportunity regarding its natural resources, and local biodiversity creates several opportunities to create novel product offerings as well as new formulation technologies, which can be exported to the EU and USA, amongst other markets. Furthermore, bespoke ingredient production using indigenous knowledge provides the opportunity to respond to a need. The indigenous knowledge system is presently underdeveloped and needs to be harnessed to give South Africa the position to be world leaders as producers of niche products. There is also major scope for developing new encapsulation techniques and formulation technologies, in order to develop superior products. These newly developed products may be more shelf-stable and also have higher efficacy. To harness this opportunity, core scientists need to increase their ability to solicit sound information from practitioners and convert this knowledge into market-ready products with demonstrated efficacy.

The characterisation of the African genome and its diversity creates an interesting space for research and development. Precision medicine therapies that are better suited to the African population can be developed, as presently, most therapies are developed using Caucasian models. The richness of the African biodiversity can as a result be used to generate insights to solve Caucasian issues. e-Health initiatives and new diagnostic development also provide other opportunities within the health biotechnology sector. The COVID-19 pandemic has unlocked several new technology leads which include vaccine manufacturing platforms for mRNA-based vaccines, as well as novel additives that may be used in vaccine formulations (Lee et al., 2021). South Africa can localise the development and production of pharmaceutical products, and once established can manufacture key drugs, especially those used in high volumes in the country.

There is also the capacity to increase localisation of biomanufacturing processes, such as biological product manufacturing in sectors other than health. At present, biomanufacturing activities are little to none, but there is capacity and capability to develop several product offerings for different applications. The country also has a vast number of experienced molecular biologists that can create “designer microbes” which can be used as production hosts which will enhance the productivity of the locally developed biomanufacturing process. As a result, precision fermentation techniques can be applied to produce target molecules demonstrating the ability of the country to generate its technologies in this regard. This sector of biotechnology also provides an opportunity for the country to conduct contract manufacturing for global partners and also license out developed technologies to other countries. Based on the experience and expertise held by certain actors within the biotechnology-based SSI, these entities could initiate novel bioreactor design, which could entail the development of cultivation and production vessels modified to suit the local landscape.

Industrial biotechnology-based initiatives can also enable the county to be more carbon-neutral (Gatto and Re, 2021), and the actors within the NSI should be more proactive in developing sustainable technologies, which includes developing lower intensity energy and water utilisation processes, the conversion of biomass to energy, capture, and sequestration of carbon, amongst others. It is vital that for all these technologies, that an eco-system-based ethos is used such that other innovations upstream or downstream from the initial technology may arise.

Precision agriculture is required to truly harness the potential of the local agricultural sector, which uses the principles of smart agriculture (Hendricks, 2011). The use of artificial intelligence and big data will enable the sector to generate knowledge to generate climate and environmental prediction models, as well as the generation of new cultivars. These new technologies will create the opportunity for biotechnology to traverse into the scope of artificial intelligence, and increase the productivity of the country in order to address the need for additional supply of agricultural commodities that are much needed by international counterparts. Agroprocessing in the country has been deemed one of the largest sectors of applicability. The country has several competitive advantages, and if developed further, can be used to increase productivity per hectare and concomitantly reducing the loss due to spoilage and damage to produce. The area of food safety is also a key area of applicability for the country, as the rest of Africa is increasing food production, however, there is a low/limited capacity to ensure traceability which limits exportability. Other than food production and processing, the South African dairy industry is at present said to be a ~R 92 billion business and technologies that upon implementation have the ability to disrupt the industry should be pursued.

It must also be mentioned that there is the explicit fact of the two different economies that are present in the country, and a window of opportunity presents itself in addressing the needs of the informal economy. Scientists and formal R&D initiatives can be applied to augment existing grass-root innovations.

4.3.7.2. Finding and accessing new markets

The South African government has created several opportunities to access both the local market as well as that of the rest of Africa. The African market itself has a lot of unrealised potential and is relatively untapped, however, more links must be created not only within the continent but also internationally.

South African technology developers need accessibility and be privy to market intelligence in order to understand demands, and possibly assess less obvious markets for suitability. The country has the ability to access the markets of the western world, including the EU and USA rather than focusing efforts on eastern markets such as India and China. 'Brexit' has also created a stimulus for transfer of technology from South Africa to the United Kingdom.

Based on the wrath of the pandemic globally, there has been a sectoral demand for health and nutrition products. Additionally, centered on the high demand for efficacious vaccines, and testing thereof, a stimulus has been created for the production of key ingredients required as raw materials. The globalisation of S&T endeavors has stimulated increased collaborations, and as a result, the international markets may be further accessed due to joint technology development, and product validations at the various locations worldwide. The existing technology platforms need to be harnessed in order to address other sector needs especially in that of the health and pharmaceutical sector as well as the clothing and textile industries. International partnerships and collaborations will by default increase market share and access to markets

R&D organisations and academic institutions should create further collaborations with established South African industries which will provide an expert view. This will allow the country to drive uptake of locally made products, including IKS-based offerings internationally. Sustainable SMME and other bio-based industry-developed models may be implemented across other African regions in order to create further impact and increase the productivity of S&T innovations across the continent, due to the realised benefits of shared learning. This learning model may also boost the productivity of African institutions in terms of skilled R&D personnel and R&D outputs.

4.3.7.3. New enabling policies

Based on the feedback from the sector participants, the existing biotechnology-based policies must be allowed to reach a state of maturity, and that implementation of policy is actually ought to be the priority. Policies need to be aligned with the development objectives of the country, and there is a need to carefully assess the S&T landscape in an attempt to identify and enforce policies that make sense. This will advocate providing solutions to the grand challenges of South Africa and also streamline innovation and commercialisation bottlenecks.

The following enabling policies may be considered to improve the status of the sector. Biofuel policies need to be better propagated such that more impact can be generated from this sector, as it is currently under-utilised. There is also an absence of policies that enforces the adoption of general green technology-based solutions such that the country adopts more sustainable practices. Additional regulations that endorse the advent of waste beneficiation opposed to the general use of landfill is required. This should also be coupled with regulations that advocate the sorting of waste prior to disposal such that more waste is recycled and reused for sustainability purposes.

Also, there needs to be an advocacy-based policy that is centered on the use of locally produced bio-actives including microorganisms. These policies should promote the use of these products as import replacements and should not only be used if lower cost is the only stimulus for uptake. The current genetic engineering, indigenous knowledge, and biodiversity acts need to be updated such that it maintains its relevance and provides a competitive advantage for the country. Policy-driven incentives for the IKS segment can be further matured such that the knowledge holders have faith and trust in the system, and would be more willing to share.

It has been recommended that SAHPRA modulates the exiting regulatory framework such that it resembles that of the US or Australian regulations, and that there is no need to reinvent the wheel in terms of policy. A major limitation is that policies are decentralised and very archaic, therefore not suitable to emerging, multidisciplinary technologies.

Policies centred on tech hubs and science parks are required to create eco-systems. There is also a need for policies that support a better risk appetite in the country. Government should be the forbearers of these changes that is required. The point where the country is now in terms of the S&T sector took ~30 years to develop, and more speed and agility are required. Policy that stimulates the biotechnology-based industry to invest in high-tech SMME startups is recommended such that technology-intensive solutions are created, and may create a more sustainable pipeline of technologies for the sector. This will promote the absorption and adoption of technology locally, as it is policy-driven.

Skills development policies, as well as policies that promote the uptake of suitably skilled individuals, are also required. Black industrialist programmes also need to be further developed such that transformation challenges may be addressed. Other non-S&T-related policies such as treasury-based exchange controls and tax incentives also need to be reinforced to support the sector.

4.3.8. Institutions

Several other findings that have emerged from these engagements across the academic, industry, and government sectors.

Academic institutions stated that useful scientific forums are being held in order to engage academics to conceptualise new projects. Also, a more concerted effort of university management is being undertaken resulting in programmes being designed to upskill and develop staff to associate professorship and professorship at the various local institutions. Some academic institutions have appointed fundraising specialists, business development managers, and commercialisation managers in an attempt to generate more impact from developed technologies and develop new technologies

Within the government sector, ministries have set up several inter-ministerial committees in order to add value and create a more cohesive and collaborative environment. This was done to delineate processes, as it has been stated that some government ministries and agencies have adopted inhibitory and restricting business practices which are inherent in its governance models. These include exhaustive due diligence processes amongst others that lead to transactional delays. It has also been noted that certain government agencies have better reputations in comparison to others. However, regardless of this, government entities have a societal contract and obligation to improve policy in order to improve socio-economic development. More relevant ministries such as the DSI has the ability to support RDI initiatives to link broader impact and therefore need to drive this agenda further.

The country is said to have word-class R&D councils. Also within these R&D institutions are respective centres that support the local biotech industry. However, further efforts must be applied in order for these centres to assist with linking actors within the NSI, as well as bridging the gap between industry and academia. It has been noted that there is a negative association pertaining to the heavy administrative burden and slow rate of efficiency when working with certain R&D councils. This slow response rate and internal processes can be improved and streamlined accordingly in order to aid the agility of the sector. On the positive side, these R&D councils have increased their accessibility to other actors within the sector. Historically, contact and communication used to be more on an ad-hoc basis, however of late, frequency and level of communication between the relevant stakeholders have increased significantly. The governance model and framework, as well as administrative processes implemented by these centres to promote a more open access facility, has proven to be a vital tool for industry actors within the sector. Furthermore, advisory panels and steering committee operating models have been adopted to facilitate and streamline these engagements. Based on its success, these mechanisms are being applied elsewhere across the country.

Biotech SMMEs have acclimatised to being responsive to stakeholders in order to uphold and streamline their efforts in terms of achieving commercial success. They are also upskilling in terms of harnessing complementary skills within the ecosystem and promote the advent of open innovation amongst peers. As the biotechnology-based SSI in South Africa is relatively small, practicing entrepreneurs have taken on the task of stimulating and mentoring other bio-entrepreneurs in leadership and technology development activities in order to assist them in manoeuvring in this space based on their past experiences. Additionally. South African SMMEs are always on the quest for better technologies that are best in the world and there isn't a mindset or room for sub-standard technology development. Local SMMEs are focused on being positioned as international businesses, and in some instances, there are dedicated individuals that are employed as business development managers in the USA, UK, and Asia – Pacific. These teams actively plan, partner, collaborate, innovate and have intuition and ingenuity in order to deliver global offerings. Additionally, the local SMMEs have become very digitally oriented and adopted new business practices. There is now an increased absence of a "shop-front" and increased levels of digital thinking and practices have been incorporated into activities, e.g., online shopping sites, etc. These local biotech-based businesses have established extensive global networks, and have a general way of drafting agreements, which is dependent on the share of efforts. E.g., 50 % input of funding revenue such that 50% risk is also absorbed. This will also incur 50% of profits. Biotech-based SMMEs, similar to other public sector agencies cannot secure loans from traditional lenders, such as banks, and therefore have limited mechanisms in securing equity stakes in certain initiatives.

Venture capital initiatives are at present, increasing in the country and are being used to build or augment companies and their initiatives in the biotech field. Grounded on the tough climate for local biotech SMMEs to operate in, resilience, kindness and a relationship-based ethos has developed amongst actors. There is also a lost arrogance with more customer-centric relationships being formed. These SMMEs are also highly cognisant and conscious of the environment and people well-being and adopt better, more environmentally friendly, and sustainable practices. The management of these SMMEs also appears to have younger more energetic teams that are thirsty and have a keen appetite for growth. They are also more responsive in the uptake of 4IR digital technologies and less risk-averse. Coupled with this, another interesting finding is that the Boards and advisory panels linked to these local SMMEs are made up of more mature and experienced individuals which thereby creates a healthy balance of perspectives. The culture of the sectors has endorsed an environment for collaboration, impact, and passion. Trust between the actors within the NSI is required in order to achieve common success. Mutual respect is an advent that featured in several interactions, stating that this encouraged collaboration and joint impact. As the landscape for biotech SMMEs is so limited in the country, active firms aims to offer personalised treatment to their customers and amend their marketing strategies away from mainstream options.

4.3.9. General findings

An overview of the study is presented in Table 4. These findings incorporate all major aspects of the study and present a synopsis of the current biotechnology-based SSI in South Africa.

Table 4. Key findings of the study

No.	Category	Description
1	**Number of active biotech firms**	South Africa had the least number of firms operating in the country in comparison to the other countries assessed.
2	**Biotech firm inter-relations**	The network diagram presented in Figure 11 shows that the firms have extensive individual networks, however, inter-firm collaborations are limited.
3	**GOVERD allocation to biotechnology**	The South African government spends more on biotech-based R&D in comparison to India and Mexico, however, the impact generated from this spend is not directly attributed to the investment made
4	**Venture capital**	The VC climate in South Africa is still relatively non-existent, however, improvements have been noted upon the entrance of OneBio to the VC landscape in the country.
5	**Business expenditure on R&D (BERD)**	South African business only spends ~0.35% of GDP on biotech-based R&D. the value that could be generated in the sector in terms of revenue and impact needs to be further highlighted nationally, in order to stimulate further investment in the sector. The network map presented in Figure 11 further illustrates that industry is generally far removed from the central region of the biotech SSI in South

		Africa.
6	**Researchers in the biotech sector**	There is still a relatively low number of biotech researchers employed on a full-time basis in South Africa. Although improvement in this regard has been noted, there can be further efforts can be made.
7	**The value generated from the biotech sector in the country**	Even though the South African government makes investments into biotech-based R&D, there is limited value generated by this industry that directly contributes to GDP. This could be a factor that contributes to the limited participation of South African industry in the sector as well as the limited number of researchers that work in the field. This finding indicates that the public understanding of the industry and its potential impact is still relatively unknown and untapped.
8	**Initial public offering (IPO)**	There are no IPOs listed in South Africa pertaining to IPOs. This was a stark finding in comparison to frontier biotech nations
9	**Patent output**	Patent output is relatively low in terms of global standing. Furthermore, biotech firms in South Africa have a low appetite to patent their technologies as they are costly and long administration processes are required. However, this creates a risk to local firms in terms of protecting their intellectual property.

10	**Publications**	South African firms and researchers publish good quality research in peer-reviewed journals, however, the output is still considerably lower in terms of global standing.
11	**University outputs**	Publications are the most common output generated by South African universities as they are incentivised for this. No incentives are in place that would change the mindset of academics to commercialise technologies and encourage the creation of spin-out companies.
12	**Commercially available products**	South African biotech firms create commercially available products that are distributed globally, indicating product efficacy and conformance to global quality standards.
13	**Policy landscape**	South Africa has some good enabling policies in place, however, a more integrated, enabling policy landscape is required to support the local biotech industry. Policies that could enable the country to be world leaders in certain technology offerings need to be fast-tracked in order to assist firms in achieving local and global success
14	**Policy implementation**	A true implementation agency/body is required to operationalize policies that are passed. There are several enabling policies in place, however, implementation thereof is severely lacking.

15	**Regulatory bodies**	These agencies need to increase responsiveness and agility to declutter processes to adequately support the sector.
16	**Fragmented NSI**	Although South Africa has world-class academic institutions, R&D councils, adequate government, and industry support, the NSI is siloed in nature and little to no collaborative activities are in place. This is a major requirement for improvement.
17	**Dynamic vs static relationships**	Based on the network assessment, very few dynamic relationships were identified. This aspect of SSI enhancement ought to be a major priority for the country.
18	**Technological capability**	South African universities, R&D councils, and firms are capable of generating world-class technologies and are currently one of the leading countries on the continent in terms of biotech-based R&D outputs.
19	**Commercialisation**	Translating technology into a commercial success is a rare occurrence in the country. At present, this occurs on an ad-hoc basis and no true execution plan or enabling mechanisms are explicitly available.
20	**Indigenous knowledge systems and biodiversity**	This sector provides a major area of opportunity for the country and needs to be advocated in terms of making new technology and product offerings to the world using indigenous knowledge and the local biodiversity.

21	**Skills and expertise**	South Africa generates a large number of high-quality biotechnology graduates. However, complementary skill sets are required especially in the area of downstream processing and product formulation
22	**Funding availability**	Biotech R&D and technology development have long horizons, and usually, there isn't sufficient funding available from one source to last throughout the development period. Therefore, different strategies need to be applied in order to supplement core R&D funding provided by the public sector with other sources such as industry investment, use of traditional lenders as well and venture capital options.
23	**Organisational capability**	This is a major limitation within the biotech-based SSI. Activities occur on an ad-hoc basis and a more synergistic approach is required in order to offer the country a chance in attaining catch-up
24	**Infrastructure**	The country demonstrates pockets of excellence in terms of infrastructure, but there have also been a few white elephants that have resulted over time. A more open access model is required to support biotech-based firms and create a more cohesive NSI
25	**The current state of the sector**	Although there have been major strides in advancing the local biotech sector, there are still major limitations and inadequacies that exist. The lack of a COVID-19 response, other than the sequencing of the new variant at KRISP,

		has highlighted the true state of the local biotech sector in terms of global standing.

In addition to the findings listed in Table 4, upon interaction with key stakeholders, it was noted that some universities are making big strides in encouraging innovation and commercialisation practices by researchers by using suitable incentive schemes. This change, however, has to be driven by university leadership in order to adjust conventional academic outputs to those that are more commercialisation in nature. Also, it has been noted that commercial and entrepreneurial skills are lacking in science degree curricula. Furthermore, the TTOs of universities is a lost opportunity in terms of generating a pipeline of commercialisation opportunities from the country's universities.

TIA has implemented the introduction of technology stations at South African Universities in order to enable student outputs and postgraduate student support. However, TIA itself has its challenges in that its own policies prevent it from maximising its potential, in terms of impact. Its vision, mission, mandate, investment frameworks that have been implemented have reduced the agility and reach of the entity, and it is also lacking a knowledge management function, and monitoring and evaluation component of its directive.

Another option for impact would be the rolling out of additional technology hubs such as the Innovation Hub. Since its inception in 2013, it has supported ~110 start-ups, with ~16 of those operating as sustainable companies. The country needs to be wary of using a plug-and-play model and bringing in foreign concepts to local shores.

South Africa is ideally located for algal biotechnology, however, actors within the NSI are not maximising the opportunity. There are international consortia that are setting up shop in the country, despite the country having its own algal pilot facilities located in the Northern Cape. This facility, despite its applicability for use, is currently non-operational, under the custodianship of TIA.

In terms of regulation, there is a limited pool of guideline-based resources available in this regard, however, regulatory bodies require these guidelines to be in place in order to assess innovations. This in some instances forces companies to take more IKS based innovations down the route of complementary medicines instead of mainstream healthcare products.

There is a lack of knowledge and understanding of how to survive the valley of death, and is also a misalignment of expectations, whereby people that have decision-making powers have different views from what exactly the experiences are "on the ground". The government of South Africa has the opportunity to lax control as politics stifle outputs. It has also been known to try and solve grand challenges instead of focusing on developing a healthy innovation system, and may not have a functional mechanism in place to incentivise grass-root innovations. Due to the socio-economic challenges faced by the country based on its past, it is often found that transformation targets and socio-economic directives are conflicting with pure science outputs.

The public sector funders must realise that the biotechnology-based technology development horizon is at least five years, and ways to limit risk and create a more non-adverse risk environment must be considered, such that failures are accepted and used as a learning tool. Other funding sources such as venture capitalists, may be considered, however, VC funds are not that large in South Africa. Lobbying of other government entities would be a good strategy in terms of creating a startup fund. OneBio has been operating for ~ 12 months, and has been previously involved in business acceleration and networking since 2017. VC funds managed by OneBio at present in South Africa are ~R 83.5 M raised from TIA and SA SME Fund, to invest in mostly seed-stage biotech ventures. OneBio operates in using two forms of support, (i) traditional VC, and take a stake in the company and (ii) venture building wherein the team comes up with an idea and puts the necessary individuals with the necessary skill-set in developing the idea further.

Areas of opportunities lie with aligning the countries skills development plan with the economic recovery plan. Skilled R&D staff is abundant, however, other skills such as technicians, artisans, and downstream specialists are also required. The country should aim to bureaucracy, IP, and exchange policies to get the country more functional, and perhaps use Latin American models to emulate due to commonalities.

CHAPTER 5: ANALYSIS OF THE RESEARCH FINDINGS

5.1. INTRODUCTION

This chapter focuses on the analysis of data presented in Chapter Four. This was further augmented by the knowledge obtained and insights gained during the compilation of the literature review presented in Chapter Two.

The analysis focuses on three key areas,

(i) The assessment of the South African biotechnology sectoral system of innovation in comparison to the six identified countries
(ii) The innovation outputs produced by the country, as well as the policy landscape and commercialisation activities
(iii) The identified pathways for catch-up and windows of opportunity

The findings of the study compared and contrasted with those found in the literature, in an attempt the answer each of the research questions.

5.2. BACKGROUND

The mixed-methods study design described in Chapter Three was used to conduct this study. The combination of descriptive statistics and primary data collection through interviews with study respondents were presented in Chapter Four, which focused on the potential of the biotechnology-based sectoral system of innovation to achieve technological and economic catch-up in South Africa.

5.3 THE ASSESSMENT OF THE SOUTH AFRICAN BIOTECHNOLOGY SECTORAL SYSTEM OF INNOVATION

Biotechnology has been identified as a key industry to provide sustainable growth of several industries and determines the competitiveness of countries as well as their economic growth (Lee & Kim, 2021). As a late-industrialising country, it was expected that South Africa would not fare as well as frontier nations in terms of the indicators identified in Chapter Four, and would perhaps be far off the mark in terms of catching up with other countries. The factors included the number of operational biotechnology-based firms, GOVERD allocation specific to biotechnology, VC allocation as a percentage of GDP specific to biotechnology, BERD allocation specific to biotechnology, the total number of researchers involved in biotechnology-specific R&D, as well as the value-added magnitude of the biotechnology industry in national currency. The biotech sector in South Africa is still relatively young, and due to catch-up being a learning process, it occurs over a lengthy period and differs across various sectors (Malerba & Nelson, 2011).

South Africa is said to have excellent researchers and facilities, good infrastructure, and a relatively sound regulatory system in comparison to the rest of the continent (Motari et al., 2004). In reports presented by Motari et al. (2004), it was stated that there were 1.88 full-time equivalent researchers per 1 000 employed South Africans. These numbers were relatively low at that time, and the situation has improved marginally, as 2019 data indicates that the sector employs ~42500 researchers (HSRC, 2018; Motari et al., 2004; OECD, 2020).

In the National Biotechnology Survey conducted in 2003, it was reported that there were ~106 biotechnology-based firms operating in the country. Of these, ~47 firms were listed as core biotechnology firms. Findings reported in Figure 2 presented in Chapter 4 stated that this number increased marginally to ~55 firms by 2013. Based on the amount invested in biotech R&D, a higher number of firms would be expected. Figure 3 in Chapter 4 shows that from the period 2009 to 2016, the GOVERD spend on the South African government on biotech-based R&D was more than that of both Mexico and India. Based on these figures, the outputs of these countries in terms of the number of biotech-based firms operating exceeded South Africa by ~10 and ~15 fold respectively. However, upon assessment of the per capita data, South Africa was on par with Mexico in terms of this respect, however, India exceeded this number of firms in comparison to both countries.

The process of learning and catching up involves understanding the similarities and differences between industries in different regions These include the differences in technologies used in various sectors of the economy, the types of customers involved, the type of competition endured, the skill set required to conduct the necessary activities as well the necessary firm-level organisation and management thereof. Other items of key influence include the nature and type of interactions between industries and universities as well as the alignment of governmental policies that can be utilised to create additional levels of support (Malerba & Nelson, 2011).

At present, South Africa differs in terms of the extent to which it provides the conditions required to develop its biotechnology industries, and this varies from case to case. A major finding of this study inferred that a more synergistic approach is required in order to make headway into achieving successful catch-up. At present, the reality of several firms operating in the space is that there is a lack of a cohesive approach to attain success as efforts are highly fragmented and secluded. This is despite the healthy proportion of skilled researchers in the field, world-class infrastructure, and government support in terms of R&D funding and policy support being in place. Several other factors at both the sectoral and country-level need to be unpacked, in order to streamline and bolster efforts in this sector. Another key finding is that in the developed world, the majority of biotech finance is supplied by the private sector (Martin et al., 2021), whereas, in South Africa, more public sector funds are spent on these initiatives.

The USA has always been considered the frontier nation in biotechnology and has the highest number of operating biotech firms, as shown in Figure 2 in Chapter 4 (Martin et al., 2021; Phillips, 2019). Firms, together with their accumulation of learning and capabilities are central to the catch-up process. Other than just having a large number of firms operating in the sector, the USA is known for creating inter-organisational partnerships between the various actors which allows for open innovation and access to specific knowledge sources. Lee and Kim (2021), stated that knowledge stocks are a main driver of the biotechnology sector, and it leads to the creation of a dynamic and competitive environment, which allows US-based firms to gain a global advantage (JMSd et al., 2021). The outcome of these networks is evident in the USA's position as the leading nation in terms of its biotech sector. Conversely, in South Africa, these networks are waning, and as a result, underperforming as outputs are limited in comparison to the rest of the world, and other developing countries. The siloed nature of the NSI is a key contributor to the current situation as the networks between the actors that comprise the triple helix hold the main sources of innovation. The USA was also the top performer in terms of available venture capital provided in the biotech sector presented in Figure 4 of Chapter 4. Despite the risk of biotech-based technology development, there has been an increase in capital being raised to support these ventures (Grislain, 2016). Regardless of the global boom in VC investment in biotech initiatives, South Africa's VC efforts are still diminutive, with only one entity, OneBio operating in this regard.

Germany's biotech sector ranks as the second-best performing country in Europe behind the United Kingdom (Philippidis, 2018). However, the efforts of the German sector may knock the UK off its perch, as the average growth rate of the sector between 2013 and 2018 was reported by Martin et al. (2021) to be at 10% in comparison to the UK's growth rate of 6%. In 2018, the market size of the German biotech industry, which is made up primarily of pharmaceuticals, environmental and industrial biotechnology endeavours, was estimated at ~ €2 Billion (Martin et al., 2021). Based on OECD data, Germany has the highest number of researchers involved in this sector (~700 000). South Africa, in contrast, has only 6% of biotech-based researchers as shown in Figure 6 of Chapter 4.

India is the world's second-most populous nation, and its government has recognised the impact of the biotechnology industry and has to date invested in several initiatives (Martin et al., 2021). At present, its industry ranks amongst the top 12 globally and accounts for ~3% of the global industry. India is also recognised as a world leader in tuberculosis and measles vaccines and the value of its biotech industry is targeted to reach $150 billion in the next 4 – 5 years (Martin et al., 2021). As a fellow BRICS country, it would be anticipated that South Africa's biotech industry would compare favourably with the status of India. However, South Africa falls behind its developing nation counterpart in most of the factors evaluated in this study, in both absolute and relative terms.

Since 2000, Singapore has focussed its efforts on developing its healthcare, pharmaceutical, biotechnology, and medical technologies in order to ramp up the country's efforts in moving towards a knowledge economy. As a late-industrialising nation, Singapore has in place a dedicated economic catch-up strategy and has made significant progress in developing its biotechnology SSI (Nelson, 2004; Spillan & Rahman, 2020). In 2021, its biotechnology sector was ranked as the second most innovative country out of 54 countries studied behind the USA (www.thinkbiotech.com, 2021). The biotechnology efforts in Singapore are driven by the joint efforts of the Agency for Science, Technology, and Research (A*STAR) and the Economic Development Board (EDB) which are comparable entities to the DSI and DTIC, which are ministries held in South Africa (UKTI, 2010).

Mexico was the only upper-middle-income country that featured in the global biotechnology top 10 index (BIO, 2010; World-Bank, 2010). Its biotechnology sector is comprised mainly of human and veterinary health, as well as agro-industrial and food industries (Amaro Rosales & Natera Marín, 2020). Policies to maximise the technological capabilities of these firms require coherence at present, and there is a need to link efforts between the various actors. Mexico has more than 400 biotech-based firms in operation which is ~10 fold higher than South Africa as shown in Chapter 4, Figure 2. This is despite the South African GOVERD spend being higher than that of Mexico presented in Figure 3 of Chapter 4.

This comparative assessment provided an analysis of the performance of South Africa's biotech SSI and indicated the areas of improvement required in order for it to attempt technological and eventually, economic catch-up.

5.4 THE PERFORMANCE OF THE SOUTH AFRICAN BIOTECHNOLOGY SSI IN TERMS OF OUTPUTS, POLICY, AND COMMERCIALISATION ACTIVITIES

Scientific publications and patents have been considered as representative indicators of scientific performance in a particular science-driven sector such as biotechnology (Gastrow, 2008). Based on 2017 data, South Africa was one of the lowest-performing countries in terms of publication outputs in comparison to the other countries evaluated in this study. The US as the frontier nation produced ~680 000 publications per annum in comparison to the ~25000 generated in South Africa (OECD, 2020). Based on a per capita estimation using the 2017 data, the publication output of South Africa was ~ five-fold lower in comparison to the USA. This finding may be attributed to the nature of biotechnology-based R&D in the country, wherein publications may not be a representative measure of innovation outputs, and some firms operating in the space may opt to patent their intellectual property rather than publishing it in the public domain (Gastrow, 2008).

Upon assessment of patent data, the country's outputs in this regard were also uninspiring. Using 2017 data, 14 patents were awarded to South African inventors, which accounted for only ~0.25% of the USA's patent output alone. This patent output was much lower than the other countries assessed in this study except for Mexico, which had a similar patent output of 17.42 (OECD, 2020). Analysis of the per capita data indicated that the patent output of South Africa per 1 000 citizens was ~ 70 fold lower than that generated in the USA. This was a remarkable finding in that, since 2008, it was expected that the pipeline of IP generated in South Africa would result in a higher output of patents as R&D expenditure increased.

In the study by Cloete et al. (2006), it was anticipated that the rate of patents would increase based on the increased emphasis on the biotechnology sector in the country. In 2008, 54 patents were recorded, and to date, this output has declined to ~ 15 per annum up until 2017 (Gastrow, 2008; OECD, 2020). However, to date, South Africa still generates very low outputs of patents in comparison to other developing countries as depicted in Figure 9 in Chapter 4. This number has decreased to ~ 14 per annum in comparison to the 58 reported by Cloete et al. (2006). This may occur due to the high costs associated with patenting. Of all the respondents tested in this study, only two participants, one an SMME and one from academia, made mention of holding patents listed in Table 2 in Chapter 4.

Due to the time period and value of the investment that is required to conduct biotechnology-based R&D, it is vital that products and technological innovations are secured such that competition is stifled. This hinders the possibility of the product being reverse engineered (www.thinkbiotech.com, 2021). However, in South Africa, firms that generate biotech-related IP do not have the appetite to patent as it is said to be a long and costly exercise. This perception of IP protection is evident based on the low number of patents generated in South Africa in comparison to the rest of the global biotechnology sector coupled to the feedback obtained from the interviewee participation during this study, which is presented in Table 2 in Chapter 4. IP protection mechanisms, other than simply keeping the knowledge generated as a trade secret or know-how does not give R&D financiers the guarantee of investment protection. The costs incurred will also be less likely to be recovered if the IP is made available in the public domain. Future considerations should be made on how best to protect South African generated IP using alternative protection mechanisms.

In 2006, the South African government was reported to spend ~ $53.3 million on R&D expenditure in comparison to $14.2 billion spent by the USA. Albeit minuscule in comparison to frontier nations, this amount fared relatively well in comparison to other developing countries, such as Poland, that spent ~$5 million on R&D activity (Gastrow, 2008). Based on survey data collected by CeSTII in 2005/6, South Africa was said to have spent R 454 million on biotechnology-based R&D in one year, this was, however, only ~3% of the country's total R&D budget (Gastrow, 2008). These budgets have increased over time, as the R&D expenditure was reported to be ~R 1. 797 billion in 2017/18 (HSRC, 2018). A widely-used strategy in other regions involves the advent of venture capital to supplement the funding available from the public sector. A key finding in this study indicated that South Africa is said to have low levels of venture capital (VC) available for biotechnology-based start-ups. In the study conducted by Motari et al. (2004), it was stated that only one VC firm, Bioventures, was operating in the country. To date, 17 years later Bioventures is said to be fully invested, and only one other VC firm, OneBio is in operation in the country. VC provides a major source of finance in the developed world. In 2013, the US was said to have a VC fund coffer of ~$368 million which was distributed to ~20 companies (Festel & Rammer, 2015). Biotech companies in the US, are reported to obtain ~R285 million investment each, yet the total fund for OneBio at present is ~ R 84 million. VC in South Africa needs significant development such that more benefits from the sector may be realised.

There are, however, highlights that need acknowledgement to demonstrate the potential of the biotechnology sector. Based on survey data presented in the annual Survey of Research and Experimental Development Inputs carried out by CeSTII, it was said that higher education institutes and research councils such as the ARC and CSIR were the key performers in the biotechnology industry and several innovations have attained the commercial status and have been implemented globally (Gastrow, 2008). Based on the findings of the network diagram presented in Figure 11 in Chapter 4, it can be seen that these institutes provide vertices for innovation and collaborative activities that have a direct impact on the number and nature of innovation outputs generated in the country.

In terms of policy in place, the landscape may add some complexities. Based on the history of the county and the impact of the apartheid years, biotechnology was not considered a state priority and received little to no support. This sector of the economy only started gaining momentum post-democracy as it was identified by the new government as an avenue to address the socio-economic challenges faced by the country, which included the creation of new industries, economic growth, job opportunities, and food security (Cloete et al., 2006).

These opportunities led to the adoption of the 2001 National Biotechnology strategy, which has over the years been substituted by the latest bioeconomy strategy in 2013 as well the 2019 White Paper on Science and Technology. The 2001 strategy had led to the development of the BRICs in 2002, which was allocated ~ R450 million to establish biotechnology-based initiatives which focused on human health, plant biotechnology, mining, agriculture, and environmental applications (Cloete et al., 2006; Gastrow, 2008). Although BRICs played a role in stimulating biotechnology-based initiatives in the country, their impact was limited as it was said to neglect small business and start-ups, and the legislative environment was not mature enough at that stage to fully support the sector (Gastrow, 2008). Although, at the time of the initiation of the BRICs, the landscape in terms of skills, infrastructure, and policy enablement may not have been mature enough to truly create successes. However, these findings lead to the notion that the idea of the BRICs centres was not in vain, but was perhaps initiated prematurely. Based on geographical location, most institutes are located in Gauteng and the Western Cape, and thus reinvigorating the notion that biotechnology-based clusters may be pursued in terms of utilising collaboration networks, infrastructure, and bolstering commercialisation efforts.

In terms of developing suitable technologies, in 2004, it was reported by Motari et al. (2004) that there has been a large effort in terms of developing R&D, both in academia and in science councils, however, a limited amount was converted into products. Since the report by Cloete et al. (2006) was published, coupled with the feedback provided by the respondents in the present study, there has been very limited improvement in this regard. This is a particularly stark finding, as all academic respondents stated that no products were commercialised from individual R&D initiatives. This finding is predominantly explained by the fact that academics are at present, only incentivised to generate publications and are therefore not inclined to produce outputs that are more commercial in nature.

Based on engagements with the study respondents, it has been made apparent that other than a lack of commercialisation outputs and the siloed nature of the sector, it is still difficult to conduct biotechnology-based business in the country, in comparison to other African countries, as well as globally. This presents a clear indication that a policy environment that is supportive of large industry is required in the country, aside from the current focus that is placed on developing small business initiatives in the biotechnology sector (Gastrow, 2008).

Prior data indicates that most biotechnology-based start-ups and SMMEs are South African-owned, and there are only a few instances of foreign-owned organisations. This finding describes the limitation of the sector as these local and international collaborations are what stimulate the required innovation outputs. In general, most of the collaborations between businesses occur with local HEIs, and science councils and only a few international partnerships are listed. Internationalisation has enabled the generation of global opportunities, but a more concerted effort in this regard is required to improve on its biotechnology-based innovation outputs.

5.5 THE PATHWAYS FOR CATCH-UP AND WINDOWS OF OPPORTUNITY

There is a global intent of moving towards a knowledge economy which moves the individual countries away from primary economic activities such as mining and agriculture into more value-added goods and services. Biotechnology forms a key component of this knowledge economy, but in 2009, South Africa’s biotech industry was reported to be non-existent (Jordaan, 2009). Yet, it has been established globally, that this sector is able to contribute towards main economic sectors such as health, energy, and agriculture (Erbas & Memis, 2012).

Development economists have a central question relating to what mechanisms may be used, or have been used by developing nations in order to “catch-up” and need to understand the technological learning that occurred and mastery attained by such successful nations (Nelson, 2007). Technological learning in its true engineering sense, not only refers to considerations required for a nation to catch-up, aspects of organisational structures and management of operations are also critical factors required to enable catch-up. In the South African biotechnology SSI, a few instances of technological catch-up have been identified, in that local firms have generated products and processes that out-compete frontier nations and technologies. However, due to the disorganised operational environment present in the sector, the opportunities to achieve commercial success are few and far between. Several study respondents have commented on the siloed, disjointed efforts of strategies implemented in the country, and therefore, the sector has not truly reaped the rewards of its efforts. Other than mere technological catch-up it is pertinent that other aspects of national education and training programs, regulatory and competition policies, capital and labour markets infrastructure support programs, and a more agile government framework are put in place such that a more credible attempt at catch-up can be made. Table 3 presented in Chapter 4, lists a number of enabling and impeding policies that are applicable to this sector. At present, a truly enabling ecosystem for biotechnology-based economic catch-up cannot be realised in the short term, as it has been stated by Nelson (2007), that the most difficult part of the catch-up process is the advent of building new institutions as well as retrofitting old institutions to new purposes.

Lee and Malerba (2017), explains that latecomer firms replace their incumbents and emerge as leaders, only to be dethroned by "new-er" entrants in catch up scenarios. In many instances, catch-up cycles may employ the harnessing of a particular window of opportunity, which was first described by Soete (1988). Several study participants stated their view on how South Africa could harness particular technological, demand, or institutional windows of opportunity to attain catch-up. These potential avenues are outlined in Chapter Four, Section 4.3.7. However, it is important to note that if the latecomer does not develop high-level capabilities together with developing local technologies, production capabilities, and healthy, collaborative R&D systems within the biotechnology SSI, then sustained growth and innovation will not be maintained, and its position may be lost to new entrants. In this instance of not maintaining and maximising catch-up cycles, latecomer nations such as South Africa may be predisposed to getting stuck in a middle-income trap (Lee & Malerba, 2017)

Based on the location of the country, an abundance of natural resources, rich biodiversity, land availability, skilled and unskilled labour, South Africa and Africa, in general provide a playground for bioeconomy-based RD&I. Bioeconomy development offers a suitable opportunity for sustainable economic growth, especially to developing countries which have an abundance of natural resources (Bracco et al., 2018). In South Africa, in particular, the development of a bioeconomy and related technologies has been highlighted by the government as a key strategy for economic growth, and in 2013, released its Bioeconomy strategy (DST, 2013). However, existing legal frameworks do not adequately cover this sector (Motari et al., 2004). Several study participants have reported on their specific activities and the relevant links to the national Bioeconomy strategy, but a noteworthy view presented by most of the study participants is that due to the lack of an identified implementation entity, that the strategy remains largely underutilised.

Bioeconomy development in South Africa can not only provide mechanisms for economic development and industrialisation, but it can also support the social objectives in the country. Based on the performance of the sector in its current state, the sector has already demonstrated inklings of success based on technological capabilities. If other aspects of catch-up are addressed, there is hope for this potential to be truly realised.

5.6 ANALYSIS OF UNEXPECTED FINDINGS

At the onset of this study, it was envisaged that pathways for catch-up could be identified and delineated, thereby creating a basis for further success in the biotechnology sector of South Africa. Findings revealed the stark reality of the sector, which highlighted major limitations that prevent leading firms and start-ups alike, to maximise commercialisation and economic success based on their leading technological innovations. Patra and Muchie (2017), amongst others, have explicitly outlined the potential of the South African biotechnology sector to grow. However, since 2017, minimal progress has been achieved in this regard. The South African sector is still relatively small in comparison to other BRICS countries and is not typically considered a global leader in terms of biotech-based R&D. Even technological successes that ought to have gained world renown, have not to date, attained nearly as much global fanfare as those attained by other frontier nations such as the USA and Germany. Findings portrayed in the study conducted by Patra and Muchie (2017) which assessed the biotech SSI in South Africa, bear a strong resemblance to the findings contained herein, demonstrating the lagging, lack-lustre performance of the industry. Four years on, stronger university-industry linkages are still waning, and need significant improvement in order to augment the chances of South Africa attaining technological and economic success.

Archibugi, Howells, and Michie (1999) stated, some 22 years ago that in order for firms and institutions of countries to be globally competitive, entities need to be innovative, technologically dynamic, and organisationally efficient in a dynamic and not static sense. As a consequence, if South Africa continues on the current trajectory, and does not place emphasis on enabling mechanisms, in particular improving organisational efficiencies, then in another 20 years, there will be no significant changes in the sector to report on, despite its promise of creating real, sustainable change to the societal and economic landscape of the country.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. INTRODUCTION

Technological and economic catch-up in the biotechnology SSI in South Africa presents an attractive, yet logical approach to be undertaken by the country. Based on its pockets of excellence and few instances of success, the sector still presents an opportunity for South Africa to overcome its socio-economic grand challenges, despite the unambiguous findings presented in this study.

6.2. MAJOR FINDINGS

Understanding the specificities of a particular country in terms of its level of economic development and reasons for the country's current economic plight need to be ascertained prior to and in addition to simply using a benchmarking approach to other countries in terms of attaining catch-up (Nelson, 2007). Based on South Africa's history and several grand challenges that exist, as a result, there are no other countries that can be used as a benchmark. Furthermore, alternate catch-up models are also not available to South Africa to employ and emulate.

Collaboration, learning, and development undertaken abroad, and exchange of human capital is imperative in a country's effort to attain catch-up. This has been demonstrated in several instances by Japan, US, Korean and Taiwanese firms whereby networks and interactions were made with frontier nations, which enabled transnational learning by the then-developing nations (Nelson, 2007). The South African government may be able to facilitate this learning and development by hosting more student exchange programmes, or also by facilitating more support for businesses in this regard. Government initiatives are key in terms of enabling a country to catch-up. This is not only in the instances of policy support, direct or indirect subsidies, and infant industry protection (Nelson, 2007). Intellectual property rights and the protection thereof are also critical for developing nations to catch-up with frontier nations. Historically, these leading nations used IP enforcement to limit the activities of developing nations in the name of infringement, although this has to some extent been restricted by the initiation of international treaties.

Additionally, South Africa must improve efforts in obtaining a more synergistic NSI in order to effectively catch up. Based on the view of respondents, it is not technological catch-up that South Africa needs to aspire to, but more organisational and institutional innovation. A less isolated and fragmented NSI must be established in order for economic development to attain a positive trajectory. It is then, perhaps, that South Africa may be able to attain technological catch-up in the biotech sector, which may have a direct contribution to eventual economic catch-up.

Other items for consideration involve the formation of regional centres in addition to The Innovation Hub as most biotech activities are at present clustered around Gauteng, KZN, and the Western Cape. In general, the public understanding of biotechnology and its intricacies is still relatively unknown, although the COVID-19 pandemic, has improved this understanding, albeit marginally.

6.3. RECOMMENDATIONS

It is recommended that more national programmes that stimulate and facilitate national biotech programmes involving academia, R&D councils, and industry are required to promote a more collaborative environment within the biotech sector. Without a national drive for these interactions and engagements, the other efforts put in place are somewhat futile.

Furthermore, a more cohesive policy landscape is required, not only for biotech-related policies, but also others relating to tax incentives and exchange controls amongst others. To date, the South African government has made significant strides in improving the small business environment in the country. However, this may have occurred at the expense of large industries. There are major improvements required at present in order for both local and international firms to operate more seamlessly, and for local firms to effectively acquire knowledge spill-overs during interactions with international firms.

6.4 LIMITATIONS OF THE RESEARCH

Due to the intricacies of the sector, clear-cut strategies for how South Africa could attain either technological or economic catch-up, or ultimately both within the sector cannot be elucidated.

6.5. SUGGESTIONS FOR FUTURE RESEARCH

Further research could involve a case study approach, wherein, a few examples of technological catch-up may be investigated further to understand the system in a more nuanced manner, to more explicitly underscore those dimensions that are still deficient. The various actors identified in these studies may then be able to further develop in those specific areas in order to achieve a wider level of success.

REFERENCES

Acemoglu, D., Robinson, J. A., & Verdier, T. (2017). Asymmetric growth and institutions in an interdependent world. *Journal of Political Economy, 125*(5), 1245-1305.

Adebowale, B. A., Diyamett, B., Lema, R., & Oyelaran-Oyeyinka, O. (2014). Innovation research and economic development in Africa. *African Journal of Science, Technology, Innovation and Development, 6*(5), V-XI.

Amaro Rosales, M., & Natera Marín, J. M. (2020). Technological capabilities accumulation and internationalization strategies of Mexican biotech firms: a multi case study from agro-food & pharma industries. *Economics of innovation and New Technology, 29*(7), 720-739.

Ammenwerth, E., Iller, C., & Mansmann, U. (2003). Can evaluation studies benefit from triangulation? A case study. *International Journal of Medical Informatics, 70*(2-3), 237-248.

Andreoni, A., & Tregenna, F. (2021). The middle-income trap and premature deindustrialization in South Africa. *Structural transformation in South Africa: The challenges of inclusive industrial development in a middle-income country*, 237-260.

Archibugi, D., Denni, M., & Filippetti, A. (2009). The technological capabilities of nations: The state of the art of synthetic indicators. *Technological forecasting and social change, 76*(7), 917-931.

Arocena, R., & Sutz, J. (2000). Looking at national systems of innovation from the South. *Industry and Innovation, 7*(1), 55-75.

AUDA-NEPAD. (2019). African Innovation Outlook. Acemoglu, D., Robinson, J. A., & Verdier, T. (2017). Asymmetric growth and institutions in an interdependent world. *Journal of Political Economy, 125*(5), 1245-1305.

Adebowale, B. A., Diyamett, B., Lema, R., & Oyelaran-Oyeyinka, O. (2014). Innovation research and economic development in Africa. *African Journal of Science, Technology, Innovation and Development, 6*(5), V-XI.

Amaro Rosales, M., & Natera Marín, J. M. (2020). Technological capabilities accumulation and internationalization strategies of Mexican biotech firms: a multi case study from agro-food & pharma industries. *Economics of innovation and New Technology, 29*(7), 720-739.

Ammenwerth, E., Iller, C., & Mansmann, U. (2003). Can evaluation studies benefit from triangulation? A case study. *International Journal of Medical Informatics, 70*(2-3), 237-248.

Archibugi, D., Denni, M., & Filippetti, A. (2009). The technological capabilities of nations: The state of the art of synthetic indicators. *Technological forecasting and social change, 76*(7), 917-931.

Archibugi, D., Howells, J., & Michie, J. (1999). Innovation systems in a global economy. *Technology analysis & strategic management, 11*(4), 527-539.

Arocena, R., & Sutz, J. (2000). Looking at national systems of innovation from the South. *Industry and Innovation, 7*(1), 55-75.

AUDA-NEPAD. (2019). African Innovation Outlook.

Bartels, F. L., Koria, R., & Vitali, E. (2016). Barriers to innovation: the case of Ghana and implications for developing countries. *Triple Helix, 3*(1), 12.

Beaubien, J. (2018). The Country With the Worlds Worst Inequality is. *National Public Radio*.

Bento, N., & Fontes, M. (2015). The construction of a new technological innovation system in a follower country: Wind energy in Portugal. *Technological forecasting and social change, 99*, 197-210.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy, 37*(3), 407-429. doi:https://doi.org/10.1016/j.respol.2007.12.003

BIO. (2010). Biotechnology in Mexico. Retrieved from https://archive.bio.org/articles/biotechnology-mexico

Bracco, S., Calicioglu, O., Gomez San Juan, M., & Flammini, A. (2018). Assessing the contribution of bioeconomy to the total economy: A review of national frameworks. *Sustainability, 10*(6), 1698.

Bullinger, H.-J., Auernhammer, K., & Gomeringer, A. (2004). Managing innovation networks in the knowledge-driven economy. *International Journal of Production Research, 42*(17), 3337-3353.

Chaminade, C., & Vang, J. (2008). Globalisation of knowledge production and regional innovation policy: Supporting specialized hubs in the Bangalore software industry. *Research policy, 10*(37), 1684-1696.

Chaturvedi, S. (2007). Exploring interlinkages between national and sectoral innovation systems for rapid technological catch-up: case of Indian biopharmaceutical industry. *Technology analysis & strategic management, 19*(5), 643-657.

Cho, D.-S., Hyun, E., & Lee, S. H. (2007). Can newly industrializing economies catch up in the science-based industries? A study of the Korean biotechnology sector. *Journal of Interdisciplinary Economics, 18*(2-3), 177-201.

Christensen-Institute. (2019). Key Concepts. Retrieved from https://www.christenseninstitute.org/key-concepts/

Cloete, T. E., Nel, L. H., & Theron, J. (2006). Biotechnology in South Africa. *TRENDS in Biotechnology, 24*(12), 557-562.

Cooke, P. (2002). Biotechnology clusters as regional, sectoral innovation systems. *International Regional Science Review, 25*(1), 8-37.

Darabi, F., & Clark, M. (2013). *Developing a general analytical inductive qualitative research strategy to investigate business school-industry collaboration.* Paper presented at the Proceedings of the 12th European Conference on Research Methods: ECRM 2013.

Dosi, G. J. R. p. (1982). Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. *J Research policy, 11*(3), 147-162.

Drucker, P. F. (1998). The discipline of innovation. *Leader to Leader, 1998*(9), 13-15.

DSI. (2019). *SOUTH AFRICA FORESIGHT EXERCISE FOR SCIENCE, TECHNOLOGY AND INNOVATION*. Retrieved from https://www.dst.gov.za/index.php/resource-center/strategies-and-reports/2977-south-africa-foresight-exercise-for-science-technology-and-innovation-synthesis-report-2019

DST. (2008). *The Ten-Year Plan for Science and Technology*. Retrieved from https://www.dst.gov.za/images/pdfs/The%20Ten-Year%20Plan%20for%20Science%20and%20Technology.pdf

DST. (2013). *The Bio-economy Strategy is an initiative of the Department of Science and Technology, South Africa.* Retrieved from Pretoria:

DST. (2019). White Paper on Science, Technology and Innovation March 2019. Retrieved from https://www.dst.gov.za/images/2019/White_paper_web_copyv1.pdf

Dubois, O., & Gomez San Juan, M. (2016). How sustainability is addressed in official bioeconomy strategies at international, national and regional levels: An overview. *Environment and Natural Resources Management. Working Paper (FAO) eng no. 63*.

Erbas, B. C., & Memis, S. A. (2012). An economic valuation of a biotechnology R&D project in a developing economy. *Electronic Journal of Biotechnology, 15*(3), 1-1.

Fagerberg, J., & Godinho, M. M. (2004). *Innovation and catching-up*.

Fagerberg, J., & Srholec, M. (2005). Catching up: what are the critical factors for success. *Vienna, UNIDO, Background paper for the UNIDO Industrial Development Report*.

Felipe, J., Abdon, A., & Kumar, U. (2012). Tracking the middle-income trap: What is it, who is in it, and why? *Levy Economics Institute, Working Paper*(715).

Festel, G., & Rammer, C. (2015). Importance of venture capital investors for the industrial biotechnology industry. *Journal of Commercial Biotechnology, 21*(2).

Freeman, C. J. C. J. o. e. (1995). The 'National System of Innovation'in historical perspective. *19*(1), 5-24.

Fusch, P., Fusch, G. E., & Ness, L. R. (2018). Denzin's paradigm shift: Revisiting triangulation in qualitative research. *Journal of Social Change, 10*(1), 2.

Gatto, F., & Re, I. (2021). Circular bioeconomy business models to overcome the valley of death. A systematic statistical analysis of studies and projects in emerging bio-based technologies and trends linked to the SME instrument support. *Sustainability*, *13*(4), 1899.

Galindo, M.-Á., & Méndez, M. T. (2014). Entrepreneurship, economic growth, and innovation: Are feedback effects at work? *Journal of Business Research, 67*(5), 825-829.

Gastrow, M. (2008). Great expectations: the state of biotechnology research and development in South Africa. *African Journal of Biotechnology, 7*(4).

GCIS. (2018). Official Guide to South Africa 2017/18. Retrieved from https://www.gcis.gov.za/sites/default/files/docs/resourcecentre/pocketguide/1-South%20Africa%20at%20a%20Glance-1718.pdf

George, A. L., & Bennett, A. (2005). *Case studies and theory development in the social sciences*: mit Press.

Godin, B. J. S., Technology,. (2006). The linear model of innovation: The historical construction of an analytical framework. *31*(6), 639-667.

Grislain, J.-H. (2016). *The venture capital in the biotechnology industry.* Massachusetts Institute of Technology,

Guo, L., Zhang, M. Y., Dodgson, M., Gann, D., & Hong, C. (2016). *Windows of Opportunity, Technological Innovation, and Globalization: Huawei's Global Catch-up.* Paper presented at the Academy of Management Proceedings.

Harsh, M., Woodson, T. S., Cozzens, S., Wetmore, J. M., Soumonni, O., Cortes, R. J. S., & Policy, P. (2017). The role of emerging technologies in inclusive innovation: the case of nanotechnology in South Africa. *45*(5), 597-607.

Hekkert, M., Negro, S., Heimeriks, G., & Harmsen, R. (2011). Technological innovation system analysis. *Technological innovation system analysis,(November), 16*.

Henderson, J. V., Squires, T., Storeygard, A., & Weil, D. (2018). The global distribution of economic activity: nature, history, and the role of trade. *The Quarterly Journal of Economics, 133*(1), 357-406.

Hendriks, J. (2011). *An analysis of precision agriculture in the South African summer grain producing areas* (Doctoral dissertation, North-West University).

Hobday, M. (2005). Firm-level innovation models: perspectives on research in developed and developing countries. *Technology analysis & strategic management, 17*(2), 121-146.

HSRC. (2018). SOUTH AFRICAN NATIONAL SURVEY OF RESEARCH AND EXPERIMENTAL DEVELOPMENT. 123. Retrieved from SOUTH AFRICAN NATIONAL SURVEY OF RESEARCH AND EXPERIMENTAL DEVELOPMENT

Iizuka, M., & Thutupalli, A. (2014). *Globalization, the rise of biotechnology and catching up in agricultural innovation: The case of Bt technology in India*. Retrieved from

IOL. (2019). *Economy.* Retrieved from https://www.iol.co.za/business-report/economy/sa-unemployment-rises-to-29-30063699

Ivankova, N. V. (2002). A sample mixed methods dissertation proposal. *Education, 48*(1), 93-135.

Jacobsson, S., & Bergek, A. (2006). A framework for guiding policy-makers intervening in emerging innovation systems in 'catching-up'countries. *The European Journal of Development Research, 18*(4), 687-707.

JMSd, A., da Costa, P., Pigola, A., Kniess, C., Porto, G., de Paulo, A., . . . dos Santos, A. (2021). Scientific Production on Technological Cooperation Networks in Biotechnology sector.

Jordaan, D. W. (2009). How to grow the South African biotechnology sector. *Essays Innovate, 3*, 42-43.

Jordaan, D. W. (2016). Biotech Innovation in South Africa: Twenty Years in Review. *Biotechnology Law Report, 35*(1), 37-42.

Kansteiner, K., & König, S. (2020). *The role (s) of qualitative content analysis in mixed methods research designs.* Paper presented at the Forum Qualitative Sozialforschung/Forum: Qualitative Social Research.

Kivimaa, P., & Kern, F. (2016). Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Research policy, 45*(1), 205-217.

Klein, M., & Sauer, A. (2016). *Celebrating 30 years of innovation system research: What you need to know about innovation systems*. Retrieved from

Laranja, M., Uyarra, E., & Flanagan, K. (2008). Policies for science, technology and innovation: Translating rationales into regional policies in a multi-level setting. *Research policy, 37*(5), 823-835.

Lee, Y., Ng, M., Daniel, K., & Wayne, E. (2021). Rapid growth in the COVID-19 era. *Mrs Bulletin*, 1-7.

Lee, & Kim, D. H. (2021). Knowledge stocks, government R&D, institutional factors and innovation: evidence from biotechnology patent data. *Innovation and Development*, 1-19.

Lee, K. (2005). Making a Technological Catch‐up: Barriers and opportunities. *Asian Journal of Technology Innovation, 13*(2), 97-131.

Lee, K. (2013). *Schumpeterian analysis of economic catch-up: Knowledge, path-creation, and the middle-income trap*: Cambridge University Press.

Lee, K. (2019). *The art of economic catch-up: Barriers, detours and leapfrogging in innovation systems*: Cambridge University Press.

Lee, K., & Lim, C. (2001). Technological regimes, catching-up and leapfrogging: findings from the Korean industries. *Research policy, 30*(3), 459-483.

Lee, K., & Malerba, F. (2013). *Successive changes in industrial leadership and the catching up by latecomers: Toward a theory of catch-up cycles from studies of selective sectors.* Paper presented at the Globelics conference, Ankara, Turkey.

Lee, K., & Malerba, F. (2017). Catch-up cycles and changes in industrial leadership: Windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research policy, 46*(2), 338-351.

Lee, K., & Malerba, F. (2018). Economic catch-up by latecomers as an evolutionary process. *Modern Evolutionary Economics: An Overview*, 172-207.

Lee, K., & Mathews, J. (2013). Science, technology and innovation for sustainable development. *CDP Background Paper Series*(16).

Leydesdorff, L. (2000). The triple helix: an evolutionary model of innovations. *Research policy, 29*(2), 243-255.

Lundvall, B.-Å., Johnson, B., Andersen, E. S., & Dalum, B. J. R. p. (2002). National systems of production, innovation and competence building. *31*(2), 213-231.

Lundvall, B. Å. (2007). National innovation systems—analytical concept and development tool. *Industry and Innovation, 14*(1), 95-119.

Malerba, F. (2005). Sectoral systems of innovation: a framework for linking innovation to the knowledge base, structure and dynamics of sectors. *Economics of innovation and New Technology, 14*(1-2), 63-82.

Malerba, F., & Mani, S. (2009). Sectoral systems of innovation and production in developing countries: an introduction. *Sectoral Systems of Innovation and Production in Developing Countries: Actors, Structure and Evolution*, 3-24.

Malerba, F., & Nelson, R. (2011). Learning and catching up in different sectoral systems: evidence from six industries. *Industrial and corporate change, 20*(6), 1645-1675.

Malerba, F., & Orsenigo, L. J. C. J. o. E. (1995). Schumpeterian patterns of innovation. *19*(1), 47-65.

Martin, D. K., Vicente, O., Beccari, T., Kellermayer, M., Koller, M., Lal, R., . . . Tapaloaga, D. (2021). A brief overview of global biotechnology. *Biotechnology & Biotechnological Equipment, 35*(sup1), S5-S14.

Mathews, J. A. (2002). Competitive advantages of the latecomer firm: A resource-based account of industrial catch-up strategies. *Asia Pacific journal of management, 19*(4), 467-488.

Mathews, J. A. (2003). Competitive dynamics and economic learning: an extended resource ‐ based view. *Industrial and corporate change, 12*(1), 115-145.

Motari, M., Quach, U., Thorsteinsdóttir, H., Martin, D. K., Daar, A. S., & Singer, P. A. (2004). South Africa—blazing a trail for African biotechnology. *Nature Biotechnology, 22*(12), DC37-DC41.

Mroczkowski, T., & Elms, H. (2009). Tracking progress: Two approaches to biotechnology development–Cases from Central Europe. *Journal of Commercial Biotechnology, 15*(3), 227-235.

Mulder, M., & Henschel, T. (2003). National biotech survey 2003. *Idea to Industry, Prepared for eGoli BIO and Department of Science and Technology, South Africa (eGoli BIO), Pinelands Office Park, Modderfontein, South Africa*.

NACI. (2013). *South African Science and Technology Indicators* Retrieved from http://www.naci.org.za/wp-content/uploads/South-African-Sceince-and-Technology-Indicators-2013.pdf

NACI. (2019). *SOUTH AFRICAN SCIENCE, TECHNOLOGY AND INNOVATION INDICATORS*. Retrieved from http://www.naci.org.za/wp-content/uploads/2019/10/South-African-Science-Technology-and-Innovation-Indicators-Report-2019.pdf

Naidoo, D. (2009). The Technology Innovation Agency (TIA): a public support mechanism for technological innovation in a developing country: research notes/commentaries. *African Journal of Science, Technology, Innovation and Development, 1*(2_3), 235-242.

Nelson, R. R. (2004). *The Changing Institutional Requirements for Technological and Economic Catch Up.* Paper presented at the DRUID Summer Conference.

Nelson, R. R. (2007). The changing institutional requirements for technological and economic catch up. *International Journal of Technological Learning, Innovation and Development, 1*(1), 4-12.

Nelson, R. R. (2008). Economic development from the perspective of evolutionary economic theory. *Oxford Development Studies, 36*(1), 9-21.

OECD. (2018). Guidelines for collecting, reporting and using data on innovation. In: OECD Publishing: Paris, France.

OECD. (2020). Key biotechnology indicators. Retrieved from http://www.oecd.org/sti/keybiotechnologyindicators.htm

OECD/Eurostat. (2005). Oslo Manual.

Onyango, G., & Ondiek, J. O. (2022). Open innovation during the COVID-19 pandemic policy responses in South Africa and Kenya. *Politics & Policy*, *50*(5), 1008-1031.

Oyelaran-Oyeyinka, B. (2014). The state and innovation policy in Africa. *African Journal of Science, Technology, Innovation and Development, 6*(5), 481-496.

Pack, H., & Nelson, R. R. (1999). *The Asian miracle and modern growth theory*: The World Bank.

Park, K.-H., & Lee, K. (2006). Linking the technological regime to the technological catch-up: analyzing Korea and Taiwan using the US patent data. *Industrial and corporate change, 15*(4), 715-753.

Patel, S. (2015). The research paradigm–methodology, epistemology and ontology–explained in simple language. *July 15th. Available at: http://salmapatel. co. uk/academia/the-research-paradigm-methodologyepistemology-and-ontology-explained-in-simple-language (Accessed: 1/6/17)*.

Patra, S. K., & Muchie, M. (2017). Role of Innovation System in Development of Biotechnology in South Africa. *Asian Biotechnology & Development Review, 19*(1).

Philippidis, A. (2018). Top 10 European Biopharma Clusters. Retrieved from https://www.genengnews.com/a-lists/top-10-european-biopharma-clusters-5/

Phillips, T. (2019). The Top Countries for Biotech Firms and Research. *The Balance*. Retrieved from https://www.thebalance.com/ranking-the-top-biotech-countries-3973287

Richardson, B. (2012). From a fossil-fuel to a biobased economy: The politics of industrial biotechnology. *Environment and Planning C: Government and Policy, 30*(2), 282-296.

Robertson, P. L., & Jacobson, D. (2011). Knowledge transfer and technology diffusion: an introduction. *Knowledge transfer and technology diffusion*, 1-34.

Robertson, P. L., & Langlois, R. N. J. R. p. (1995). Innovation, networks, and vertical integration. *24*(4), 543-562.

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*: Pearson education.

Schumpeter, J. A. (1947). The creative response in economic history. *The journal of economic history, 7*(2), 149-159.

Semete-Makokotlela, B. (2015). *Investment performance of the South African Biotechnology industry and potential financing models.*

Shoaib, S., & Mujtaba, B. G. (2016). Use it or lose it: Prudently using case study as a research and educational strategy. *American Journal of Education and Learning, 1*(2), 83-93.

Smith, A., Fressoli, M., & Thomas, H. J. J. o. C. P. (2014). Grassroots innovation movements: challenges and contributions. *63*, 114-124.

Soete, L. (1988). 2 1 Catching up in technology: entry barriers and windows of opportunity.

Soumonni, O. (2014). Schumpeterian Analysis of Economic Catch-up: Knowledge, Path-creation, and the Middle-income Trap. In: Taylor & Francis.

South Africa. Department of Arts, C., Science,, & Technology. (2001). *A national biotechnology strategy for South Africa*: The Department.

Spillan, J. E., & Rahman, M. N. (2020). The Economic Climate. In *Doing Business in Chile and Peru* (pp. 89-131): Springer.

Stevens, C. (1996). The knowledge-driven economy. *Organisation for Economic Cooperation and Development. The OECD Observer*(200), 6.

Szczygielski, K., Grabowski, W., Pamukcu, M. T., & Tandogan, V. S. (2017). Does government support for private innovation matter? Firm-level evidence from two catching-up countries. *Research policy, 46*(1), 219-237.

Tabachnick, B., & Fidell, L. (2013). Using Multivariate Statistics, 6th Edn, New International Edition. *Harlow: Pearson Education Limited*.

Tabellini, G. (2010). Culture and institutions: economic development in the regions of Europe. *Journal of the European Economic association, 8*(4), 677-716.

Tashakkori, A., & Creswell, J. W. (2007). Exploring the nature of research questions in mixed methods research. In: Sage Publications Sage CA: Los Angeles, CA.

Taylor, J., & Levitt, R. (2004). Understanding and managing systemic innovation in project-based industries. *Innovations: Project management research*, 83-99.

Thorsteinsdóttir, H., Quach, U., Daar, A.S. & Singer, P.A. Conclusions: promoting biotechnology innovation in developing countries. *Nat Biotechnol* **22** (Suppl 12), DC48–DC52 (2004). https://doi.org/10.1038/nbt1204supp-DC48

Uctu, R., & Essop, H. (2012). *The Role of the South African Government in Developing the Biotechnology Industry–from Biotechnology Regional Innovation Centres to the Technology Innovation Agency*. Retrieved from

UKTI. (2010). Sector briefing: Biotechnology & Pharmaceutical Opportunities in Singapore. 5. Retrieved from https://s3.amazonaws.com

van Wyk, R. W. (2018). *Challenges to localisation in South Africa: a case study of the molecular diagnostics and reagents sector.* University of Pretoria, Viotti, E. B. (2015). Technological learning systems, competitiveness and development.

Warwick, K. (2013). Beyond industrial policy: Emerging issues and new trends.

Watson, H., & Krishna, N. (2019). Important facts often forgotten as to SA's attractiveness to investment. Retrieved from https://www.businesslive.co.za/bd/opinion/2019-10-09-important-facts-often-forgotten-as-to-sas-attractiveness-to-investment/

Wong, P.-K. (1999). *National innovation systems for rapid technological catch-up: an analytical framework and a comparative analysis of Korea, Taiwan and Singapore.* Paper presented at the DRUID Summer Conference.

World-Bank. (2010). Innovation Policy: a guide for developing countries.

www.thinkbiotech.com. (2021). Global Biotechnology Innovation Scorecard. Retrieved from https://www.thinkbiotech.com/globalbiotech/country/Singapore#:~:text=Biotechnology%20Innovation%20Score%20Summary,Singapore%20in%20the%20overall%20rankings.

APPENDICES

APPENDIX A –Semi-structured interview questions for assessing the state of South Africa's biotechnology sectoral system of innovation

Conducted by Ghaneshree Moonsamy

Thank you for agreeing to a meet with me. The purpose of the interview is to answer Research questions on the topic "**Technological and economic catch up in the biotechnology sectoral innovation system in South Africa**". The special focus is your experience and approach to operating as a biotech firm in South Africa. I am delighted for your company to feature in this research. Please note that all information will be anonymised in this study.

Part A - Overall biotechnology sector assessment -

1. What is your role in the company/organisation?
2. What activity is your firm involved in?
3. What other company/companies/organisations does your firm work with?
    a. Which ones do you work with closely?
    b. Which ones are more occasional?
4. In your view, how does South Africa compare in terms of its technological capabilities in comparison to peer countries?

    a. What are your company's research outputs?
    b. What is your company's production capability?

Part B - Innovation-based measures -

5. What are your company's or organisation's outputs in terms of IPO, patents, products and publication outputs?

    a. Which of these are most important to your company/organisation?
    b. How many of these do you have?
    c. Which ones are most indicative of its diffusion/commercialisation potential in your experience?

5. What is your company's main instrument/technique for commercialisation (Examples may include patents, technology licensing and royalties)?

6. What has been the influence of Science, Technology and Innovation (STI)/biotech-relevant policies at either the national, provincial or local levels on your commercialisation efforts?
    a. Have any of these policies been enabling?
        i. Which ones, and how have they been enabling?
        ii. Have any of them impeded your efforts?
    b. How important is policy in enabling your company to close the productivity/sales gap with leading countries (e.g. relative to other BRICS countries and beyond)?
    c. Do these policies help in developing novel, cutting-edge technologies?

<u>Part C – operational environment</u>

7. A key component of this research study is to assess the specific environment respective to your company:

Usually an operating environment consists of three main building blocks

i. knowledge and technologies
ii. actors and networks
iii. institutions

i. knowledge and technologies:

a. Can you describe in general terms, the type of knowledge that your company/organisation needs in order to be competitive in the sector?
b. What kinds of technologies does it need to be competitive in the sector?

c. Do you have links with other companies/organisations that are more input-output based? These are described as static links.
d. Are there links with other organisations that are more dynamic? This may arise from sectoral demand and your production capability?
e. If you were to map out the links/relationships and complementarities/synergies that your company/organisation has with others? What would this map look like?

8. Actors and networks

Using a schematic, please identify the **main actors, where applicable,** that are most relevant to your activities in your specific environment.

9. Institutions

Could you please comment on whether your company/organisation has, over time, adopted behavioural characteristics such as specific norms, routines, common habits, established practices, or perhaps internal rules, policies and standards that have enabled it to significantly improve its ability to achieve its desired outcomes?

Part D: Windows of opportunity

10. What would you say are the main opportunities that may enable you to increase your productivity?
    a. Scientific novelty?
    b. Finding and accessing new markets?
    c. New enabling policies?

Closure

What are your closing comments? Could you kindly suggest any other persons who might have different perspectives, to possibly interview?

Thank you for your time, input, and for granting this interview.