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SCIENCE, TECHNOLOGY AND INNOVATION INDICATORS FOR THE BIOECONOMY IN SOUTH AFRICA: A SCIENTOMETRIC ASSESSMENT

by

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THESIS SUMMARY

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The South African Cabinet approved the South African Bioeconomy Strategy in 2013. This was followed by the launch of the Strategy in January 2014 by the Department of Science and Innovation. Bioeconomy is a recent term following the term biotechnology and encompasses activities that make use of bio-innovations based on biological sources, materials and processes to generate sustainable economic, social and environmental development. The vision is for South Africa's bioeconomy to be a significant contributor to the country's economy by 2030 in terms of the gross domestic product (GDP). This document provides science, technology and innovation indicators to monitor the implementation of the South

African Bioeconomy Strategy as recommended by the National Advisory Council on Innovation in South Africa.

The study firstly provides an analysis of bioeconomy indicators in general and discusses sources of available literature from the following databases: Web of Science, Scopus, EconLit and Social Science Premium Collection. Within the bioeconomy definition, biotechnology is a common thread, however, the scope and measuring of the bioeconomy goes beyond the technology. Efforts by countries in measuring the bioeconomy at the policy level have been based on growth measures such as the contribution to GDP, however, such an approach offers an incomplete picture as it omits the environmental and social impacts of the bioeconomy. The results from the selected journal articles highlight that most academic papers discuss indicators of social, economic and environmental sustainability, yet there remains a gap as to how these interdependent sectors should be linked in order to develop a uniform methodology to measure all the aspects included in the bioeconomy. From the conclusion, the bioeconomy can be defined as the system that contributes to economic, social and technological development and is conducted without the depletion of natural resources.

A comparison of changes in inputs as compared to changes in output over time will allow an assessment of the efficiency of the bioeconomy innovation system (e.g. if outputs grow more rapidly than inputs, the efficiency increases). The next components of the study focus on bioeconomy gross expenditure on research and development (R&D), business expenditure on R&D and the number of R&D personnel in the bioeconomy. These are key measures of inputs in the bioeconomy. The number of publications, patents and firms, and the value of exports in the bioeconomy were measured. These are key measures of outputs in the bioeconomy. The number of publications, patents and exports values are outlined for South Africa and compared with Brazil, Russia, India and China (BRICS) and, to a certain extent, with Egypt, Nigeria, Germany, Malaysia and the United States of America (USA).

The results show higher growth rates for resources committed for R&D in the bioeconomy compared to that of total research expenditures in South Africa. The growth rate for researchers in headcounts in bioeconomy were low compared to the growth rates for researchers in headcounts across all fields in South Africa. South Africa ranked last in the BRICS group in terms of the number of bioeconomy publications produced in the selected period and had a world share of 0.8%, which is higher than the national research average of 0.5%. The citations growth for South African bioeconomy publications increased by 6.8%, higher than Brazil, Russia and world citations during the period under review. The University of Cape Town is a leader in bioeconomy publications in South Africa, followed by University of Stellenbosch and the University of KwaZulu-Natal with majority of the publications on environmental sciences ecology. South Africa collaborates the most with institutions from the United States of America in bioeconomy research and the percent of international collaboration is similar to that of national scientific publications. South Africa experienced a decline in bioeconomy industry collaboration publications during this period. South Africa ranked last in the BRICS group but perfomed superior than Egypt and Nigeria in terms of the number of bioeconomy patents. The total patents citations for all BRICS members generally decreased and there were inconsistent growth rates observed. The important innovators of South Africa in this field are mainly universities and public research institutions as compared to other members of BRICS and Egypt which are dominated by private entities. Incentives that encourage collaboration between universities, research institutions and local innovation firms are required for the full realisation of South Africa’s Bioeconomy Strategy. There were 730 active bioeconomy firms in South Africa as of January 2021. South African gross exports total for bioeconomy industry sectors considered in this study were generally small compared to other members of BRICS. South Africa requires total growth of its innovative products and production processes.

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ACRONYMS AND ABBREVIATIONS

ARC	Agricultural Research Council
BERD	Business expenditure on research and development
BRICS	Brazil, Russia, India, China and South Africa
CAIA	Chemical and Allied Industries Association
CESM	Classification of Educational Subject Matter
CIPC	Companies and Intellectual Property Commission
CREST	Centre for Research on Evaluation, Science and Technology
CSIR	Council for Scientific and Industrial Research
DACST	Department of Arts, Culture, Science and Technology
DBA	Derwent Biotechnology Abstracts
DHET	Department of Higher Education and Training
DSI	Department of Science and Innovation
DST	Department of Science and Technology
EC	European Commission
EPO	European Patent Office
ESCI	Emerging Sources Citation Index
EU	European Union
FAO	Food and Agriculture Organisation
FSA	Forestry South Africa
G/LVA	Gross and/or Local Value Added
GBMSA	Generic and Biosimilar Medicines of Southern Africa
GDP	Gross Domestic Product
GERD	Gross Expenditure on Research and Development
GFCF	Gross Fixed Capital Formation
GMO	Genetically Modified Organism
HEMIS	Higher Education and Management Information System
HSRC	Human Science Research Council

IKS	Indigenous Knowledge Systems
IP	Intellectual Property
IP5	Five Intellectual Property Offices
IPASA	Innovative Pharmaceutical Association of South African
IPC	Intellectual Patent Classification
ISI	Institute for Scientific Information
MDASA	Moringa Development Association of South Africa
MINTEK	Council for Mineral Technology
NACI	National Advisory Council on Innovation
NDP	National Development Plan
NFF	New Funding Framework
NGOS	Non-Government Organisations
NIPMO	National Intellectual Property Management Office
NRF	National Research Foundation
NSI	National System of Innovation
OCED	Organisation for Economic Cooperation and Development
PATFT	Patent Full-Text and Image Database
PATSTAT	EPO Worldwide Patent Statistical Database
PCT	Patent Cooperation Treaty
PMASA	Paper Manufactures Association of South Africa
R&D	Research and Development
RMAA	Red Meat Abattoir Association
RPO	Red Meat Producers Organisation
SABO	South African Bioproducts Organisation
SAMED	South African Medical Device Industry Association
SAMRC	South African Medical Research Council
SANSOR	South African National Seed Organisation
SAPA	South Africa Poultry Association
SAPIA	South African Petroleum Industry Association
SASA	South African Sugar Association
SCI	Science Citation Index

SCISTIP	Scientometrics and Science, Technology and Innovation Policy
SDG	United Nations Sustainable Development Goals
SEOBI	SA Essential Oils Business Incubator
SIC	Standard Industrial Classification
SNA	System of National Accounts
SSPC	Social Science Premium Collection
STI	Science, Technology and Innovation
TIVA	Trade in Value Added
TYIP	Ten-Year Innovation Plan
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USA	United States of America
USD	United States Dollar
USPTO	United States Patent Office
WIPO	World Intellectual Property Organisation
WOS	Web of Science
WTO	World Trade Organisation

CHAPTER 1: INTRODUCTION

1.1 HISTORICAL DEVELOPMENT AND CURRENT STATE OF THE BIOECONOMY

South Africa is one of the strongest economies in Africa along with Nigeria and Egypt in terms of GDP (International Monetary Fund, 2021). South Africa has been grouped alongside middle-income countries such as Brazil, Russia, India and China (BRICS) to compete in the global knowledge economy. BRICS countries have been working towards closer cooperation with each other within the scientific disciplines, among others.

Since 1994 the South African Science, Technology and Innovation (STI) policy went through numerous changes. The White Paper on Science and Technology: preparing for the 21st century was formulated in 1996 (DACST, 1996). The aim was to achieve an improved and sustainable quality of life for all South Africans through science, technology and innovation. A national system of innovation (NSI) based on the core principles of partnerships, coordination, problem-solving and multi-disciplinary knowledge production was proposed through the creation of a proper regulatory and funding mechanism (DACST, 1996).

The goals of the White Paper on Science and Technology (DACST, 1996), and the Technology Foresight studies (DACST, 1999) informed the formation of the National Biotechnology Strategy in 2001 (DST, 2001). The National Biotechnology Strategy resulted in the establishment and funding of Biotechnology Regional Innovation Centres, to promote R&D, provide entrepreneurial services, technology platforms, intellectual property management and business incubation in the biotechnology sector. Under the National Biotechnology Strategy, the biotechnology sector grew slowly, with more research groups developed than firms. The strategy focused on commercialisation of technologies that were close to the market instead of developing a full innovation value chain.

The Ten-Year Innovation Plan (TYIP) 2008-2018 (DST, 2007a) was published in 2008, which aimed at transforming South Africa towards a knowledge-based economy, where the production and dissemination of knowledge leads to economic benefits and the enrichment of all fields of human endeavour. In 2010, the Ministerial Review Committee was commissioned to review the science, technology and innovation (STI) landscape in South Africa and make recommendations for the future of NSI in South Africa. The TYIP and the Ministerial Review Committee report (DST, 2012), with lessons from the National Biotechnology Strategy, informed the formulation of the National Bioeconomy Strategy in 2013 (DST, 2013).

The National Bioeconomy Strategy provides a more coordinated and integrated South African focus for the biotechnology sectors (DST, 2013). Bioeconomy is not restricted to biotechnology, but is inclusive of other disciplines such as information technology, social sciences and engineering, to create holistic solutions and industrial applications for agriculture as well as the health and industrial sectors, in order to create a world-class biotechnological system of innovation. South Africa's Bioeconomy Strategy has been formulated to be more productive, more responsive and more relevant to the needs of South Africans, and to make a marked positive impact on the lives of all South Africans. The strategy provides a high-level framework to guide biosciences research and innovation investments, as well as decision-making as South Africa adapts to the realities of global transition to a low-carbon economy, cleaner environment and the sustainable use of available resources. The strategy is designed to have a technology-push and market-pull approach, to address the country's developmental goals and needs, as well as its industrial and sector competitiveness (DST, 2013).

1.2 DEFINITION OF BIOECONOMY

Bioeconomy is a recent term following the term biotechnology. "Bioeconomy is the production, utilisation and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy" (GBS, 2018). The OECD defines bioeconomy as "a world where biotechnology contributes to a significant share of economic output" (OECD, 2009a). The German government's Bioeconomy Council (2018) defines bioeconomy as "the knowledge based production and use of biological resources to provide products, processes and services in all economic sectors within the frame of a sustainable economic system". The European Union (EU) defines bioeconomy as "the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products as well as bio-energy" (EC, 2012).

South Africa's Bioeconomy Strategy defines the term bioeconomy as "activities that make use of bio-innovations, based on biological sources, materials and processes to generate sustainable economic, social and environmental development" (DST, 2013). Definitions of bioeconomy vary depending on each country's specific economic, ecological and social demands (Lier et al., 2018; 2019). However, it is evident that the South African definition of bioeconomy is broadly in accordance with definitions employed in other bioeconomy strategies globally.

Within bioeconomy, biotechnology is a common thread. According to the OECD, (2009a), bioeconomy is likely to involve "advanced knowledge of genes and complex cell processes, renewable biomass, and the integration of biotechnology applications across sectors". Biotechnology refers to the use of biological processes, organisms or systems to provide knowledge, goods and services (Bull, Holt and Lilly, 1982; Sridhar, 2005; Chekol and Grebeyohannes, 2018). In the context of this study, biotechnology is a broad term which focusses on the development of new processes and products while bioeconomy is subsumed under the biotechnology definition, but with more focus on innovative economic activities. Thus, some of the data provided is still organised by technology field and not by economic sector.

1.3 **RESEARCH PROBLEM**

The Bioeconomy Strategy identified several indicators as elements of a bioeconomy measurement framework (DST, 2013). The NACI in South Africa, which advices the South African Minister of Science and Innovation on the role and contribution of science, mathematics, innovation and technology, among others, indicated that the Bioeconomy Strategy did not clearly outline the measurement framework to monitor the implementation of the strategy over time. The NACI established a project team to provide a complete indicators framework suitable for the measurement, evaluation and monitoring of the implementation of the strategy. The DSI, which coordinates the Bioeconomy Strategy of South Africa, contributes to the bioeconomy through the encouragement and enhancement of innovation and technological advancement. The NACI recommends that the DSI measure innovation and technological change in bioeconomy through resources committed to enhance innovation and technological change in bioeconomy; and through output measures such as the number of bioeconomy publications and citations in peer reviewed journals, the number and share of South African patents and citations in bioeconomy, and output attributed to innovation by firms in bioeconomy. This thesis seeks to investigate input measures based on R&D expenditures and the number of researchers for the bioeconomy in South Africa and output measures based on bioeconomy publications, patents, firms and exports.

1.4 RESEARCH OBJECTIVES AND QUESTIONS

The research will answer the following questions:

1.4.1 Input Measures

1. What is the gross expenditure on R&D (GERD) in biotechnology?
   This is a key measure of all resources devoted to R&D in bioeconomy. Data is available from the South African National Survey of Research and Experimental Development Statistical reports.
2. What is the business expenditure on R&D (BERD) in biotechnology?
   Business expenditures on R&D are closer to market and are more likely to generate output, employment, exports and investment than R&D done by government or higher institutions. Data is available from the South African National Survey of Research and Experimental Development Statistical reports.

3. What is the number of researchers performing R&D in fields of biotechnology? This is a key measure of input into R&D in bioeconomy. Data is sourced from HEMIS and the South African National Survey of Research and Experimental Development Statistical reports.

1.4.2 ***Output Measures***

The NACI recommends output measures be divided into three narrow categories, namely science, technology and economic outputs, and these are:

1.4.2.1 Science Outputs

1. What is the number of South African authored publications covering bioeconomy disciplines using the WoS database?
2. What is the number of citations of South African authored publications covering bioeconomy disciplines as indexed to the WoS using InCites^{TM} database?
3. What is the performance of South Africa in comparison with other BRICS countries, and to a certain extent, with Egypt, Germany, Malaysia and the United States of America?

1.4.2.2 Technology Outputs

1. What is the number and the share of South African patents in biotechnology, selected environment-related technologies, medical technology and pharmaceuticals registered in the USPTO and the EPO?
2. What is the number of citations of South African patents in biotechnology, selected environment-related technologies, medical technology and pharmaceuticals registered in the USPTO and the EPO?
3. What is the number of biotechnology, selected environment-related technologies, medical technology and pharmaceuticals patents filed with the PCT?

4. What is the number biotechnology, selected environment-related technologies, medical technology and pharmaceuticals patents that belong to the IP5 and triadic families?
5. What is the performance of South Africa in comparison with other members of the BRICS and with Egypt and Nigeria?
6. What is the number of patents in biotechnology registered in South Africa at the CIPC by South Africans?
7. What is the number of patents in biotechnology registered in South Africa at the CIPC by foreigners?

1.4.2.3 Economic Outputs

1. What is the number of firms in the bioeconomy in South Africa?
2. What is the value of bioeconomy exports? Selected bioeconomy industry sectors are used for the analysis.

Where publication data is organised by scientific field and not by economic sector, the NACI recommends the use of the term biotechnology. This is in accordance with the bioeconomy definition employed in this study, which is defined as biotechnological innovation that contributes to economic development. In such instances where the term biotechnology is used, the results are therefore a proxy for the bioeconomy.

1.5 KEY ATTRIBUTES OF THE DESIRED THEORY AND DERIVED METHODS

To generate data based on the systematic review of literature on bioeconomy indicators, the WoS, Scopus, EconLit and SSPC databases were used.

To generate bibliometrics data, the WoS and InCites™ databases were used for South African authored publications and citations respectively, covering bioeconomy disciplines and the performance compared with BRICS countries, and to a certain extent, with Egypt, Germany, Malaysia and the USA.

To generate patent data, (1) the OECD patents by technology, (2) the EPO PATSTAT and (3) the USPTO PatFT databases were used to map patents in biotechnology, selected environment-related technologies, medical technology and pharmaceuticals, the most prolific organisations and the types of institutions who are the leading innovators in these fields, and the backward, non-patent literature and forward citations at the EPO and the USPTO for BRICS , Egypt and Nigeria. The OECD patents by technology database was used to map patents in biotechnology, selected environment-related technologies, medical technology and pharmaceuticals filed with the PCT, patents that belong to the IP5 and patents that belong to the triadic families for BRICS. The CIPC Patent Search database was used to map biotechnology patents registered in South Africa by South Africans and foreign inventors.

The expenditure data on R&D is collected from the South African National Survey of Research and Experimental Development Statistical report 2017/18 (DSI, 2019). The data on the number of researchers performing R&D in fields of biotechnology is collected from HEMIS and the South African National Survey of Research and Experimental Development Statistical report 2017/18 (DSI, 2019). The data on the number of bioeconomy firms is collected from various websites and industry/business associations. Finally, the data for exports value in the bioeconomy is collected from the OECD TiVA indicators database.

The goal of this study is to describe the growth of the bioeconomy sector in South Africa by analysing publication and citation trends in the area of bioeconomy, patents and citations trend in bioeconomy, as well as bioeconomy firms and the value of exports of bioeconomy products. Bioeconomy is recent and in its infancy, and this presents the novelty of the study. The study is important in informing baseline information for the development of appropriate metrics for the measurement of progress of the Bioeconomy Strategy in South Africa. The study is important for the development of scientific, technological and innovation inputs and outputs for the measurement of progress of change in bioeconomy in South Africa.

The study begins by describing the literature on bioeconomy indicators in general and provides publication trends in the area of bioeconomy. The study then reports a desk review-based indicator analysis for the bioeconomy from source literature globally. A comparison of the changes in inputs as compared to changes in outputs over time with the selected countries will allow an assessment of the efficiency of bioeconomy system of innovation in South Africa. The study then describes the scientific and technological performance of South Africa in comparison to Brazil, Russia, India and China in bioeconomy by means of the number of publications and patents and their citations respectively in bioeconomy. For some data, Egypt, Germany, Malaysia, Nigeria and the United States of America are considered for comparison. Finally, the number of active bioeconomy firms and the value of exports of bioeconomy products for selected industries are measured. Accordingly, in addition to performance measures that assess scientific, technological and innovation outputs for bioeconomy, input measures based on R&D expenditures and R&D personnel for the bioeconomy are assessed for the complete measure of the efficiency of the bioeconomy innovation system. The study focuses on the TYIP period that is between 2008 and 2018.

The BRICS countries are selected for this purpose as they are considered five major emerging national economies, and the countries have been working towards closer cooperation between the members in various scientific disciplines. Therefore, a benchmark amongst these countries present a fair comparison. The BRICS group has previously been studied by a number of authors to compare the scientific (Bornmann, Wagner, and Leydesdorff, 2015; Makhoba and Pouris, 2016; 2017) and technological (Patra and Muchie, 2017; Makhoba and Pouris, 2019a) outputs within the group. Germany, Malaysia and USA have dedicated bioeconomy strategies (The White House, 2012; AIM, 2013; BMBF and BMEL, 2015; MOSTI and Bioeconomy Corporation, 2016) and represents multiple continents, while Egypt is the second most productive country in Africa in terms of research publications (Naravaez-Berthelemot et al., 2002) and Nigeria currently records the highest GDP in Africa (International Monetary Fund, 2021).

CHAPTER 2: LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 BACKGROUND

Expectations that bioeconomy will become a major contributor to economic growth and impact on quality of life explain its high priority globally (McCormic and Kautto, 2013; Bracco et al., 2018; Ronzon and M'Barek, 2018; Egenolf and Bringezu, 2019). Theoretical advances in understanding innovation processes and instruments for innovation policy have created an increasing demand for empirical tools to develop policy from a systems perspective (Dosso, Marting and Moncada-Paternò-Castello, 2008; Edler and Fagerberg, 2017).

Biotechnology is a broad term that covers the practical use of biological systems to provide goods and services (Bull, Holt and Lilly, 1982; Sridhar, 2005; Chekol and Grebeyohannes, 2018). Biotechnology is believed to have the ability to change the way a society lives by considering the great potential of living systems, their applications and their potential impact on the development of society as a whole (Pouris and Pouris, 2009a). Biotechnology is considered a key sector for future economic growth and it has been the main driver for the development of environmentally sustainable production practices and the development of various innovative products. Biotechnology has the potential to contribute to social development by, for example, ensuring community involvement and the protection of indigenous knowledge. This led to the development of the term bioeconomy, which is defined as economic activities derived from biological sources, materials and processes through research and innovation (McCormic and Kautto, 2013; OECD, 2009a; Henry and Trigo, 2010; DST, 2013). Definitions of bioeconomy vary depending on a country's specific economic, ecological and social demands (Lier et al., 2018). Key industrial sectors that derive their raw material and/or key components along the value chain from natural resources and biological processes constitute the bioeconomy (Lokko et al., 2018).

The concept of bioeconomy is rapidly expanding. In 2018, there were approximately 8 countries with a dedicated bioeconomy strategy, namely: Finland, Germany, Greenland, Iceland, Japan, Malaysia, South Africa and United States of America. Other countries (more than 50) had some policy elements on bioeconomy, however, they did not have a dedicated bioeconomy strategy. Currently, more and more countries are developing strategies and policies related to bioeconomy and bio-based products and industries (Staffas, Gustavsson and McCormick, 2013). By 2020, there were about 49 countries with bioeconomy strategies (Böcher et al., 2020).

The world faces a number of environmental, economic and social challenges and the bioeconomy is expected contribute to addressing these sustainable development challenges. A paper by Chavarria et al. (2020) summarises potential contributions of the bioeconomy to the sustainable development goals (SDGs). These are SDGs that contribute to sustainable food production, land use, good health and well-being, affordable and clean energy, industry and innovation, climate change mitigation, responsible consumption and production, clean water and sanitation, prevention of land degradation and socio-economic growth. However, the appropriate indicators and uniform methodology for measuring the contribution of the bioeconomy to the sustainable development goals are lacking.

2.2 BIOECONOMY POLICY IN SOUTH AFRICA

South Africa adopted a coordinated approach to develop the Bioeconomy Strategy as articulated in the National Development Plan (NDP, 2012), which requires that research and innovation by universities, science councils, government departments, non-government organisations (NGOs) and the private sector contribute to improving the country's global competitiveness. Coordination between these different role-players is suggested as one of the fundamental issues needing attention.

The Bioeconomy Strategy in South Africa, coordinated by the DSI, identified three key economic sectors that are likely to benefit from the bioeconomy; these are: agriculture, industry and environment, and health, with indigenous knowledge systems (IKS) as an important crosscutter contributing to the activities within these three sectors (DST, 2013).

The objectives of South Africa’s Bioeconomy Strategy are to make South Africa more competitive internationally, to create more sustainable jobs; to enhance food security, and to create a greener economy as the country shifts towards a low-carbon economy (DST, 2013). The strategy outlines a systems approach to be taken for the development of the bioeconomy, recognising the complex and non-linear nature of innovation and the diversity of ‘actors’, role-players, institutions, policies and regulations. The roles of the various stakeholders are ideally complementary, supportive, and additive, and it is the collective whole that contributes to the bioeconomy. Under the strategy there are a variety of priority issues listed, including the need for partnerships and coordination. In the USA bioeconomy for example, government enhances and coordinates communication between different domestic agencies and entities, and establishes protocols for the sharing of data (USDA, 2011). According to the Food and Agriculture Organisation (FAO), (FAO, 2016), however, these efforts should go hand-in-hand in the development of indicator frameworks to measure the bioeconomy and its sustainability at an international level.

2.3 REVIEW OF INDICATORS IN THE BIOECONOMY IN GENERAL

The OECD defines indicators as measurable variables which provide empirical statements on the facts to be described in a representative form (OECD, 2003). Indicators provide numerical indications of changes in highly complex and interrelated systems (DPME, 2016). Indicators should be interpreted in an integrated manner, beyond the numbers and within the broader, socio-economic context (OECD, 2000). Indicators are a collation of data extracted from many sources, including official statistics, government databases and research institutions (DPME, 2016). The indicators should provide a comprehensive overview and analysis of countries’ progress towards the realisation of their bioeconomy strategies’ visions.

There is no internationally agreed methodology to measure the bioeconomy. Given the differences among countries' grand challenges, the development of a uniform way to assess the contribution of bioeconomy across all countries is challenging (Fund et al., 2015). Proxies and indicators used to measure the bioeconomy depend on national goals and these differ between countries (Lier et al., 2018). There should be an assessment, as a coherent whole, of the current efforts of individual countries to define bioeconomy and the frameworks for measuring, monitoring, and reporting its contribution to ensure comparability of the results (Bracco et al., 2018). This is the case in the European Union (EU) where the European Commission (EC) has been assigned to monitor jobs and turnover in the EU bioeconomy for all member states and sectors, to encourage a uniform way to assess the contribution of bioeconomy in Europe.

In terms of technological advancements, generally there are both input and output measures to be considered when developing indicators. The input measures include expenditure on research, development and innovation projects, on the provision and establishment of equipment and infrastructure, and on coordinating networks. The outcomes from such investment is measured through the number of papers published, patents awarded, the number of firms established, and the value of products exported. The bioeconomy, however, looks beyond technological advancements and includes indicators on economic, social and environmental impacts. The majority of countries measure bioeconomy progress over time with only economic values, shares of GDP and employment statistics (FAO, 2018). Environmental and social impacts of bioeconomy are often foreseen, but not measured (Bracco, et al., 2018).

The indicators for input and output measures are mainly extracted from published sources, including official government statistics and international databases, such as those from the OECD, United Nations Educational, Scientific and Cultural Organisation (UNESCO), World Trade Organisation (WTO), World Bank and United Nations Conference on Trade and Development (UNCTAD), research institutions and private sector, among others. Comprehensive tools mapping the environmental and socio-economic impacts of the bioeconomy are lacking. Multidisciplinary monitoring approaches that integrate social, environmental and technological perspectives are needed to promote the development of a sustainable bioeconomy (Budzunski, Bezama and Thrän, 2017).

2.4 INDICATORS FOR THE BIOECONOMY IN SOUTH AFRICA

The Bioeconomy Strategy of South Africa identified several potential indicators as elements of a bioeconomy measurement framework (DST, 2013). The NACI indicated that the strategy did not clearly outline the measurement framework to monitor the implementation of the strategy over time. The NACI recommends that the DSI measure innovation and technological change in bioeconomy through both input and output measures. The input measures include expenditure on R&D and the number of researchers in bioeconomy in South Africa. The outcomes from such investment is measured through the number of papers published and their citations, patents awarded and their citations, the number of firms established, and the value of products exported by bioeconomy firms in the selected industry sectors. The proposed indicators are discussed in detail in the sections below.

2.5 GERD, BERD AND RESEARCHERS IN BIOECONOMY

GERD is the total amount spent on R&D by organisations in a given country (OECD, 2021). BERD is the total amount spent on R&D by business enterprises (OECD, 2017:146). Researchers in headcount means the total number of persons engaged in R&D during a specific reference period (OECD, 2015:167). The literature on GERD, BERD and researchers in headcount in South Africa is documented in national R&D surveys, the most recent being the 2018/19 survey (DSI, 2021). There are existing studies that are based on the South African National R&D surveys (Mani, 2001; Fedderke and Schirmer, 2006; Paruk et al., 2014; Mustapha et al., 2015; Walwyn and Cloete, 2016; Makhoba and Pouris, 2019b; Molotja et al., 2019; Barnabé et al., 2020). For example, Mani (2001) identified the policy instruments and institutions that developing countries can put in place to encourage more R&D investments by their respective private sectors. Their findings based on R&D surveys were that research personnel are a critical element in successfully stimulating R&D in enterprise sectors. Fedderke and Schirmer (2006) studied the R&D Performance in the manufacturing sector in South Africa for the period of 1970 to 1993 and collected the data from R&D surveys. More specific to biotechnology, Makhoba and Pouris (2019a) studied the R&D efficiency in biotechnology in South Africa and compared it with other BRICS countries. They reported that South Africa has the highest R&D efficiency in biotechnology compared to other BRICS members as measured by both patents and publications and as expressed by the GERD.

2.6 BIBLIOMETRIC ANALYSIS OF BIOECONOMY RESEARCH

Bibliometric studies provide systematic analyses of research systems across time and countries (Pereira, 2000). Bibliometric studies of biotechnology mainly focus on understanding development status and trends in terms of research publications and patents. Bibliometric studies of biotechnology date back as early as the 1980s (Rip and Courtial, 1984; Kochhar and Verma, 1987; Nordstrom, 1987; Nederhof, 1988; Singh and Saxena, 1992; Thomas, 1992; DeLooze, 1994; Lewison, 1994; Martens and Saretzki, 1994; Zucker, Darby and Brewer, 1994; McCain, 1995a; McCain, 1995b; Hinze and Grupp, 1996; DeLooze and Lemarié, 1997; DeLooze and Ramani, 1999; Banerjee, Gupta and Garg, 2000; McMillan, Narin and Deeds, 2000; DeLooze, Coronini and Joly, 2001; Leydesdorff and Heimeriks, 2001). The literature on bibliometric studies of biotechnology is mainly based on the use of the Science Citation Index (SCI) (Thomas, 1992; Zucker et al., 1994; McCain, 1995b; Leydesdorff and Heimeriks, 2001; DeLooze et al., 2001) or the Derwent Biotechnology Abstracts (DBA) databases (Kochhar and Verma, 1987; Singh and Saxena, 1992; McCain, 1995a; McCain, 1995b; Hinze and Grupp, 1996; Leydesdorff and Heimeriks, 2001; DeLooze and Ramani, 1999; Banerjee et al., 2000; McMillan et al., 2000; DeLooze et al., 2001). The SCI database was mainly used for analysis of publications while the DBA database was mainly used for analysis of patents. For example, DeLooze et al. (2001) used the SCI and DBA databases to analyse scientific publications and applications for patents in the field of genomics. Banerjee et al. (2000) used the DBA to compare the change in patenting activity in biotechnology for selected periods. Leydesdorff and Heimeriks (2001) used the SCI and title words of scientific publications in five core journals of biotechnology to distinguish between the intellectual organisation of the publications in Europe, USA and Japan. However, other researchers have used the DBA to study the literature trends in biotechnology. Singh and Saxena (1992) used the DBA database to analyse references collected in mass health care from biotechnology applications for the period of 1983 to 1987 to study the literature trend in this area.

A literature review on the use of SCI and DBA databases in bibliometrics studies in biotechnology is detailed by Dalpé (2002). The two databases are now maintained by Clarivate Analytics, through the WoS. There are several papers already documented on the use of the WoS in bibliometric studies on biotechnology. Sevukan and Sharma (2008) provided an analysis of research performance of biotechnology faculties in central universities of India from 1997 to 2006. More recently, Makhoba and Pouris (2016) investigated biotechnology publications in South Africa compared with the fields of energy, astronomy and palaeontology, using the WoS database for the period of 2002 to 2012.

There are other databases such as Scopus and Google Scholar that were recently considered by other researchers in bibliometric studies in biotechnology, however, these are not part of this study. Bajwa and Yaldram (2013) studied research trends in Pakistan in the field of biotechnology using the Scopus database for the period 1980-2011. López-Illescas, de Moya Anegón and Moed (2009) compared bibliometric country-by-country rankings derived from the WoS and Scopus in the field of oncology. Scopus is interdisciplinary and covers a wider journal range compared to the WoS, which is subject-specific (Wagner, 2015). However, Scopus is currently limited to more recent articles compared to the WoS (Falagas et al., 2008). In terms of citation, Google Scholar data is not comparable to data from other bibliometric databases such as the WoS and Scopus (Aguillo, 2012). A study by Martín and Martín et al. (2018) found that most citations found only by Google Scholar compared to WoS and Scopus were from non-journal sources as well as non-English language journals. Scopus and Google Scholar are time consuming in terms of data collection and processing compared to the WoS. In the analysis of more than 10000 citing and purportedly citing documents, the WoS data took about

100 hours of collecting and processing time. Scopus and Google Scholar took about 200 and 3000 hours respectively (Meho and Yang, 2006).

Bibliometric studies using the keyword 'bioeconomy' are still in their infancy as bioeconomy is a recent term following the term biotechnology. A paper by Bugge, Hansen and Klitkou (2016) bases the bibliometric analysis of bioeconomy on a literature retrieval of relevant scientific articles indexed from the Core Collection of WoS. They concluded that the delimitation of a sample can be defined by the chosen publishing period, the geographical location of the authors, the selection of research areas, the selection of a journal sample, or the selection of keywords. In a paper by Rodríguez-Salvador, Rio-Belver and Garechana-Anacabe (2017), the researchers used the WoS and Scopus databases to retrieve scientific publications in the field of 3D bioprinting. 3D bioprinting is used in research on pharmaceuticals, which form part of the bioeconomy. Yao et al. (2014) used the WoS to evaluate global scientific production and develop trends of health systems research from 1900 to 2012 to provide data on the current status and impact of health systems research globally. Pfau et al. (2014) used a multi-disciplinary approach for bibliometric analysis of the bioeconomy. The authors chose multiple databases in order to cover a broad range of literature that might address bioeconomy. Five databases from the fields of natural and environmental sciences, economics and social sciences were selected including the WoS to investigate the relationship between bioeconomy and sustainability by means of a systematic review. Recently, a bibliometric study on assessing the degree of openness of scientific articles on bioeconomy based on the WoS was published (Duquenne et al., 2020). The findings were that the open access articles in the field of bioeconomy have increased sharply between 2015 and 2019, with a share percentage of 45.6.

2.7 OVERVIEW OF PATENTS AND CITATIONS AND THEIR USE IN BIOECONOMY

A Patent is an invention and innovation indicator used to measure technological progress. Patents are legal instruments protecting an invention (OECD, 2009b). Patents are limited rights, valid for a maximum of 20 years after the date of application, after which the invention falls in the public domain and can be used by anyone without paying royalties. Patents are territorial rights which only apply to the country in which they are granted. A patent granted in one country will not confer exclusivity in another country, it will only prevent the patenting of the same invention in other countries as worldwide novelty is required to obtain a patent. The patent system allows transparency as they are published 18 months after filing and thus the detailed information about the latest technological advancements are available. Patent statistics can be used to measure a country's inventive activity and capacity to exploit knowledge and translate it into potential economic gains. Therefore, patent statistics allow policy makers to measure the inventive and innovative performance of a country (Eurostat, 2018).

The use of patents as technological innovation statistics is well documented (Scherer, 1965; Schmookler, 1966; Comanor and Scherer, 1969; William and Scherer, 1969; de Solla Price, 1983; Pavitt, 1985; Narin, Noma and Perry, 1987; Connolly and Hirschey, 1988; Griliches, 1990; Frame, 1991; Albert et al., 1991; Grupp and Schmod, 1998; Ramani and DeLooze, 2000; Tijssen, 2001; Crosby, 2007; Bessen, 2008; Che and Guan, 2011). These include patents studies in biotechnology (ko, 1992; DeLooze and Ramani, 1999; Banerjee et al., 2000; DeLooze et al., 2001; Dalpé, 2002; Harhoff and Reitzig, 2004; Magerman, Van Looy and Debackere, 2011; Arts, Appio and Van Looy, 2013; Guo et al., 2013; Petruzelli, Rotolo and Albino, 2014; Bordoloi and Dekah Boruah, 2018; Fukuzawa and Ida, 2016; Makhoba and Pouris, 2019a). For example, Dalpé (2002) provided the literature on patents and scientific publications in biotechnology and used the DBA database to rank leading countries and organisations in patents related to plant genetics between 1996 and 1999. The USA and organisations from the USA were leading in terms of the number of patents applications related to plant genetics during the period under investigation. DeLooze et al. (2001) used DBA database to analyse applications for patents in the field of genomics. They found the USA leading in terms of the number of patent applications in this field, while Europe had a low number of patent applications. Arts et al. (2013) identified the most important technological inventions in the field of biotechnology for the USPTO patents filed between 1976 and 2001 through the study of citation-related indicators. The authors indicated that biotechnology patents representing important technological innovations have a high number of citations to scientific publications.

Bordoloi and Dekah Boruah (2018) analysed patenting activities and organisations in the field of bioremediation of petroleum hydrocarbon from the year 2000 to 2016 for the USA, China, Korea, Japan, Russia, Great Britain, Mexico, India and Canada. The databases searched included the USPTO, the EPO, World Intellectual Property Organisation (WIPO), FREEPATENTSONLINE and Indian Patent Advanced Search System. Makhoba and Pouris (2019b) studied patent activities for BRICS countries and Egypt for the period of 2001 to 2015. The research priority areas considered were information and communication technology, nanotechnology, biotechnology, climate change, energy and health, using the WIPO database. Barragán-Ocaña et al. (2019) determined trends in biotechnology-related PCT applications in Chile, Mexico, Argentina, Brazil, and Cuba from 1999 to 2015 as well as the relationship between GERD as a percentage of GDP and PCT applications for biotechnological inventions from 2007 to 2015. The growth in biotechnology PCT applications for these countries were moderate and gradual and GERD as a percentage of GDP was found to be associated with biotechnology-related PCT applications.

As with scientific publications, patents provide references to patents or to non-patent literature such as scientific publications (van Raan, 2017). These are known as citations. Citations in patents are considered one of the important indicators measuring the technological and economic value of patents (Squicciarini, Dernis and Criscuolo, 2013). The use of patent citations in research dates back to the 1960s (Garfield, 1966; Griliches, 1979; Carpenter, Narin and Woolf, 1981; Carpenter and Narin, 1983; Narin et al., 1987; Trajtenberg, 1990a, 1990b; Hall, Jaffe and Trajtenberg, 2005; Webb et al., 2005). Patent citations are indicators of quality, originality, value, knowledge flows and impact (Griliches, 1984; Jaffe, Trajtenberg and Henderson, 1993; Harhoff, Scherer and Vopel, 2002; Jaffe and Trajtenberg, 2002; Hall et al., 2005; Gambardella, Harhoff and Verspagen, 2008; Choi and Park, 2009; Funk and Owen-Smith, 2016; Jaffe and de Rassenfosse, 2017).

Patent citations are used by policymakers in assessing the impact of innovation policies (Abrams and Sampat, 2017). Patent citations are also used by organisations to measure the strategic behaviour of a company (Podolny, Stuart and Hannan,1996). Patent citations can either be forward or backward or non-patent literature. Forward citations are the number of citations a patent receives. The number of forward citations relates to the technological importance and value of a patent (Carpenter and Narin, 1983; Trajtenberg, 1990b; Albert et al., 1991; Harhoff et al., 1999; Jaffe, Trajtenberg and Fogarty, 2000; Gittelman and Kogut, 2003; Harhoff et al., 2002; Hall et al., 2005; Gambardella et al., 2008). However, the distribution of forward citation is skewed (Arts et al., 2013). Some patents receive higher forward citations, while other patents receive little or no forward citations. While it could mean some patents are more important than other patents, the reason for this discrepancy is not clear. Further, there is a time lag effect. New patents have less forward citations than older patents and thus the forward citation counts should be truncated. The backward citations are references that a patent cites (Von Wartburg, Teichert and Rost, 2005). Referencing can either be patent references or non-patent references. Citing a previous patent is an indication of reliance on previous technology, the value of a patent and lead to the discovery of other closely related patents (Harhoff et al., 2002; Jaffe and de Rassenfosse, 2017). Non-patent literature refers to peer-reviewed scientific publications, conference proceedings, databases and other relevant literature that reflect the prior art that inventions have built upon. Citing non-patent references illustrates the promotion of knowledge diffusion and linkages between scientific research and technology development (Tijssen, 2001; Callaert et al., 2006; Funk and Owen-Smith, 2016).

Magerman, van Looy, B and Debackere (2015) investigated the impact of patenting in the dissemination of a researcher's scientific publications by means of citation analysis of patent paper pairs in biotechnology using text-mining algorithms. Their investigation included 948,432 scientific publications and 88,248 patent documents from the EPO and the USPTO. It was found that publications linked to a patent receive more citations than publications without a patent link. Both forward and backward citations have limitations in that patent examiners contribute to patent citations, and thus not all citations originate from the applicant. Alcácer, Gittelman and Sampat (2009) found that examiner citations account for 63% of all citations on the average patent, and that 40% of patents have all citations added by examiners. Patents offices such as the EPO and the USPTO have begun reporting examiner and applicant citations separately.

The use of patents citations in bioeconomy is still underdeveloped. Li, Chen, and Wu (2007) provided a simple regression model that can be used to predict citations to biotechnology patents from the front pages of patent documents. Petruzelli et al. (2014) studied the determinants of patent citations in biotechnology on a sample of 5,671 patents granted at the USPTO to 293 USA biotechnology firms from 1976 to 2003. Their findings show that the use of scientific knowledge negatively affects patent influence outside the biotechnology industry, while it positively contributes to a patent's increased relevance for the assignee's subsequent technological developments. The broader the scope of a patent the higher the number of citations the patent receives.

2.8 PATENTS IN SOUTH AFRICA

In South Africa, patenting is regulated under the South African Patent Act 57 of 1978 and the CIPC is the custodian of patents applications in South Africa. Patenting in South Africa is documented (Pouris and Pouris, 2011) in detail. South Africa does not have an examination process for patents registration. Applicants should confirm the novelty and validity of the invention on submission.

2.9 OVERVIEW OF FIRMS AND EXPORTS IN THE BIOECONOMY IN SOUTH AFRICA

2.9.1 The number of active bioeconomy firms in South Africa

The literature on firms' outputs in biotechnology is limited and mainly based on countries' national surveys, for which most of the data is available from the OECD Biotechnology Statistics database. South Africa, through the DSI, published findings from National Biotechnology Audits in 2003 and 2007, with respect to the number of firms active in biotechnology, expenditures on firms' R&D, employment in the sector, sales by biotechnology firms, and the number of biotechnology firms by application in South Africa (DST, 2003; 2007). The response rates were 72 and 81 percent respectively. In the 2007 survey, the target population consisted of 241 firms (DST, 2007b). South Africa had 78 biotechnology firms of which 38 were identified as dedicated biotechnology firms – an increase from 47 core and 59 non-core biotechnology firms in the 2003 survey. According to the OECD (van Beuzekom and Arundel, 2009), a Biotechnology firm is "a firm that uses biotechnology to produce goods or services and/or to perform biotechnology R&D", while a dedicated biotechnology firm is "a biotechnology firm whose predominant activity involves the application of biotechnology techniques to produce goods or services and/or to perform biotechnology R&D". In other countries, there are also biotechnology firms who perform R&D only, and R&D firms that devote 75% or more of their total R&D to biotechnology R&D.

In a recent study, Patra and Muchie (2017) investigated the number of firms in the life sciences in South Africa using various websites and different membership directories. They developed a database of about 692 firms in the life sciences of which 279 were foreign firms. Brazil published the number of Biotechnology R&D firms from their country at the OECD key biotechnology indicators database under the number of firms active in the biotechnology, 2006-2018, the total biotechnology firms. The surveys in Brazil were conducted for 2011, 2014 and 2017 and recorded 160, 309 and 190 Biotechnology R&D firms respectively. Notably, Brazil recorded 71 dedicated biotechnology firms in 2006 (van Beuzekom and Arundel, 2009). Data for other members of the BRICS group is not available on the OECD key biotechnology indicators database.

2.9.1.1 Export measures

The Bioeconomy Strategy envisages that South Africa would become more competitive internationally (DST, 2013:3). The bioeconomy places emphasis on the trade balance and balance of payments i.e. on exports minus imports for bioeconomy products. In order to assess the success of the South African bioeconomy, NACI suggests that an increase in bioeconomy exports will be one of the key indicators of the success of the Bioeconomy Strategy. According to NACI, the major contribution of the bioeconomy will be in enhancing innovation and raising competitiveness, resulting in more bioeconomy exports. This suggestion is well documented in the literature (Wakelin, 1998; Aylward, 2004; Pla-Barber and Alegre, 2007; Chadha, 2009; Van Beveren and Vandenbussche, 2010; Palangkaraya, 2012), to name a few. For example, the authors Pla-Barber and Alegre (2007) studied 121 firms in the French biotechnology industry to analyse the link between export intensity and innovation, and they concluded that there is a positive and significant link between export intensity and innovation, and that the size of the firm in science-based industries such as biotechnology does not affect export performance.

The paper by Palangkaraya (2012) found a positive correlation between export and innovation in the same period from Australia's Small and Medium Enterprises. A similar observation is recorded in the pharmaceutical industry in India by investigating the export performance of 131 Indian pharmaceutical firms for the period of 1989 to 2004 using patents (Chadha, 2009). The size of the firm does not necessarily correlate with export performance. The paper by Moen's (1999) showed that science-based small firms can perform satisfactorily in global markets and be competitive against large companies. Plehn-Dujowich (2009) found small firms to be more innovative than large firms based on patent counts and citations per dollar of R&D. From these observations, it is evident that innovation at the firm correlates with the firm's export performance, and the size of the firm does not necessarily correlate with export performance.

The literature on export measures in the bioeconomy is not available, however, NACI STI annual indicators surveys reports on merchandise exports by technological intensity for the different industries in South Africa based on data from the UNCTAD (NACI, 2018; 2019). Notably, some of the industries reported on includes the agro, medicinal and pharmaceutical products which the bioeconomy contributes. Of concern, however, are the sectoral boundaries of the bioeconomy. Bioeconomy cuts across sectors and therefore cannot be treated as a traditional sector. Different sectors and subsectors composing the bioeconomy are not easily identifiable (Wesseler and von Braun, 2017). Many current attempts distinguish sectors by their dependence on bio-based resources as inputs to production processes (Piotrowski et al., 2015; Efken et al., 2016; Ronzon et al., 2017). Most bioeconomy strategies encompass the agricultural sector, food sector, pulp and paper, as well as the pharmaceuticals, chemicals, plastics and textiles sectors, etc. based on bio-based resources. Most indicators in the bioeconomy include the whole agricultural sector, as well as the whole user sectors of biomass, such as food as well as pulp and paper, when calculating economic figures (Piotrowski, Carus and Carrez, 2015; Ronzon et al., 2017).

In conclusion, most of the data on indicators for the bioeconomy are readily available. It is however critical to understand the scope of the bioeconomy for a particular country under investigation and selected industries that make use of bioeconomy applications in their production and processes. The data can be generated or collected from academic research databases, published sources, official government statistics, industry associations and international databases, such as those from the OECD, UNESCO, WTO, UNCTAD, EPO, USPTO, among others.

CHAPTER 3: THEORETICAL FRAMEWORK

The theoretical framework approach proposed in this study is based on linear and non-linear models of innovation. The bioeconomy indicators should be based on all aspects of the innovation value chain, taking into account the linear and non-linear nature of the value chains, as well as the links within the value chains. The methods proposed in this study for development of the bioeconomy indicators are both qualitative and quantitative in nature. The research first considers the literature available on bioeconomy indicators in general. The second aspect of the research measures the bioeconomy in terms of quantified innovative activities, and these are: innovation expenditures, innovation process, and results and performance. A quantitative approach to bioeconomy is important in monitoring and measuring of progress of implementation of the bioeconomy in South Africa.

3.1 BIOECONOMY CONCEPT

The South African Cabinet approved the South African Bioeconomy Strategy in 2013. This was followed by the launch of the Strategy in January 2014 by the DSI. The concept of the bioeconomy has been rising steadily up the political agenda. Bioeconomy is a recent term following the term biotechnology, and is defined in the National Bioeconomy Strategy as “activities that make use of bio-innovations, based on biological sources, materials and processes to generate sustainable economic, social and environmental development”. Biotechnology and bioeconomy are said to be interrelated. However, their links are not clearly established (Befort, 2020). In context to this study, biotechnology is a broad definition which focusses on the development of new processes and products while bioeconomy is subsumed under the biotechnology definition, but with more focus on innovative socio-economic activities. An innovation is defined by the OECD (OECD 2018a:20) as “a new or improved product or process (or combination thereof) that differs significantly from the unit’s previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)”. The bioeconomy is expected to provide solutions to most socio-economic challenges through the development of new or improved products or processes. However, the development of innovation indicators to track and measure the bioeconomy remain a challenge. Most of the innovation data is still organised according to the technology and not by the economic sector. In addition to the technology, as articulated by Befort (2020), the bioeconomy should also consider biomass and sustainability in its definition, which makes it even more complex to measure. In the bioeconomy the entire innovation system or network, ranging from ideas, research, development, productisation and manufacturing to commercialisation, should be followed to realise the bioeconomy's full potential in a coordinated manner. This approach is known as the linear model of innovation (Fig. 1). The model suggest that innovation starts with basic research (invention), is followed by applied R&D (innovation), and ends with production and diffusion (commercialisation). This is in order to understand the relation of science and technology to the economy (Godin 2006).

Figure 1: *Linear model of innovation (Own illustration)*

The original source of the linear model is not clear. Several authors have used, improved, or criticised the model (Rogers, 2003:102-134; Kline and Rosenberg, 1986; Godin, 2006; Balconi, Brusoni and Orsenigo, 2010). Godin (2006) studied the history of the linear model, suggesting that it developed in three steps corresponding to three scientific communities looking at science analytically. The article argues that statistics is a main reason the model is still being used despite criticisms, alternatives, and having been proclaimed dead. Kline and Rosenberg (1986) argue that the process of innovation is not necessarily linear but an interactive process, relying on both the development process and feedback from the market. Balconi et al. (2010) discusses the strength and weaknesses of linear model of innovation and reviews the model criticisms in the literature. The authors concluded that the model is still useful in science-based industries and policy areas. The model may complement more general theories which recognise innovation process to be dynamic and interactive in nature. An example of a non-linear innovation value chain is depicted in the National Bioeconomy Strategy (Fig. 2)

(DST, 2013:11), and based on Cooper (1990) and Hart et al. (2003)'s frameworks, among others.

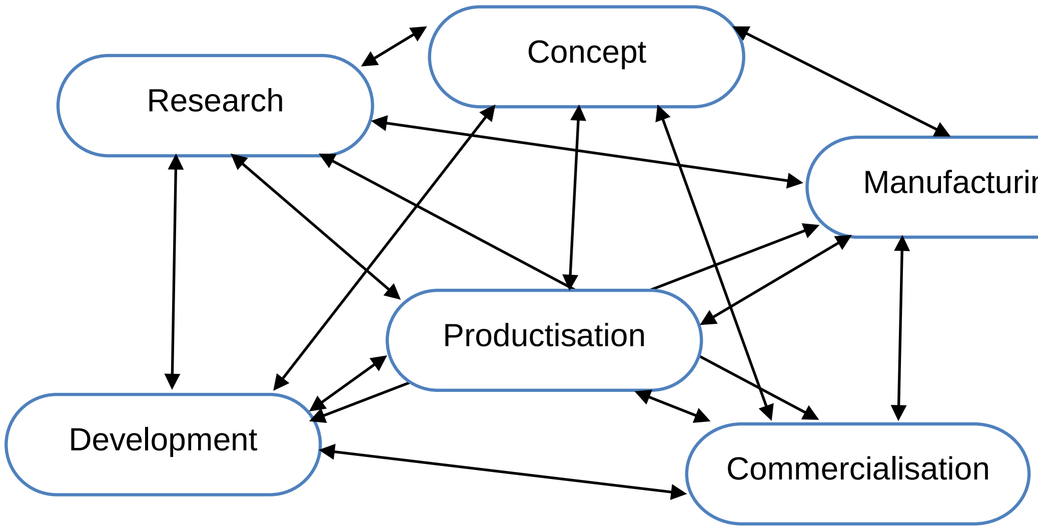


Figure 2: Non-linear innovation value chain (Source: adapted from the National Bioeconomy Strategy (DST 2013:11)

The non-linear model takes into account that the network between different stages of innovation are interlinked. The model may reflect that of triple, quadruple, and quintuple helices in its structure (Mikhaylova, 2014). The model starts with formulation of the idea against market needs, which leads to formulation of research. Research results are developed as pilots and tested to ensure success of the proof of concept. The technology is packaged in the form of a product acceptable for the market and a prototype is developed that can be manufactured. The product is manufactured and business activities take place (DST, 2013:11). Non-linear models are closer to the real innovation process compared to linear models and offer better understanding of qualitative changes that occur in the economy. The linear model is, however, easy to construct and has been widely used in the quantitative evaluation of scientific, technological and innovation capabilities in the economy (Mikhaylova, 2014).

3.2 **PROPOSED INDICATORS**

Indicators are "measurable variables which provide empirical statements on the facts to be described in a representative form" (OECD, 2003). Borrás and Edquist

(2013) define innovation indicators as “the source of information from which one can detect problems in the innovation system”.

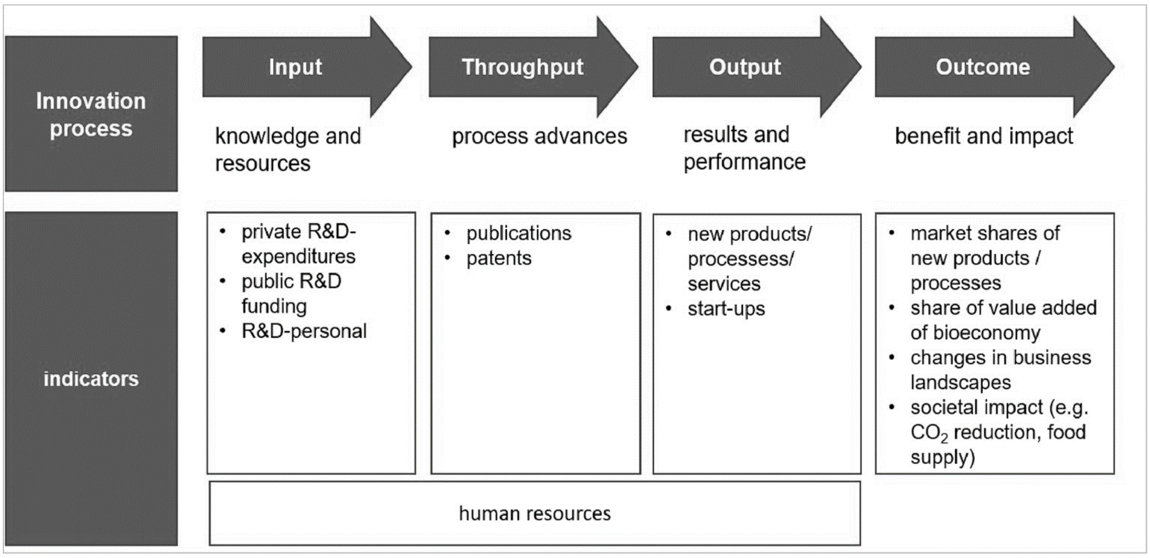


Figure 3: Innovation indicators along the innovation process (Source: Wydra 2020).

There are studies documented that discuss or attempt to measure indicators in the bioeconomy (Efken et al., 2016; Parisi and Ronzon, 2016; Ronzon et al., 2017; Wesseler and von Braun, 2017; Bracco et al., 2018; Biber-Freudenberger et al., 2018; Dietz et al., 2018; Lier et al., 2018; Ronzon and M’barek, 2018; Egenolf and Bringezu, 2019; Loizou et al., 2019; Wen et al., 2019). These studies provide insights on the conceptualisation of the measurement of the bioeconomy in terms of jobs, turnover, GDP, estimations of the bio-based shares and the measure of sustainability in the bioeconomy. The data is mainly focused on socio-economic indicators for the bioeconomy and provides little on innovation indicators for the bioeconomy. Wydra (2020) provides a framework that could be used to develop innovation indicators along the innovation process in the bioeconomy (Fig. 3). The framework discusses input and throughput indicators for the bioeconomy in Germany. A similar approach as with that of Wydra (2020) is proposed for the measurement of indicators for the bioeconomy as a whole in South Africa (Fig. 4) and for the development of innovation indicators for the bioeconomy in South Africa (Fig. 5.). The proposed metrics for the bioeconomy as a whole are: 1) investment based on gross fixed capital formation for the bioeconomy, 2) bioeconomy share of national gross domestic product, 3) growth rate based on turnover and sales, 4) bioeconomy exports, and 5) total employment in the bioeconomy. Indicators for transformation such as race, gender and age groups, addressing the South African triple challenges of poverty, unemployment and inequality are critical and will also need to be measured.

The diagram in Fig. 5 illustrates the measures and important steps in the innovation process in the bioeconomy and the indicators proposed for each stage. The model follows that of Wydra (2020) above. Innovation is divided into four sub-stages: knowledge and resources, process, results and performance, and benefit and impact. The indicators to measure knowledge and resources devoted to R&D in the innovation process include: Gross expenditure on R&D, Business expenditure on R&D, and personnel in R&D. Process indicators are publications and patents. Indicators for results and performance include bioeconomy companies and products or services commercialised.

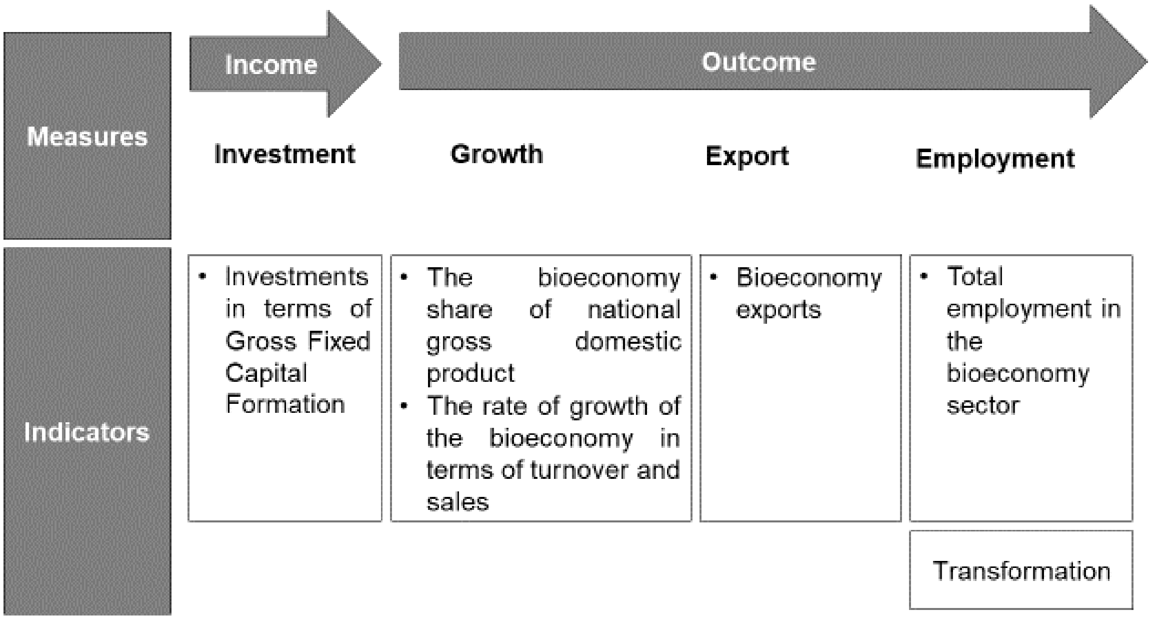


Figure 4: Potential indicators for the bioeconomy as a whole in South Africa. (Source: own illustration adapted from Wydra (2020)).

Lastly, the benefit and impact indicators are indicators that measure exports and the value of exports for products such as in pharmaceuticals and medical instruments, agriculture, forestry and fisheries, food and beverages, and pulp and paper. The development of innovation indicators for the bioeconomy should complement indicators for the bioeconomy as a whole.

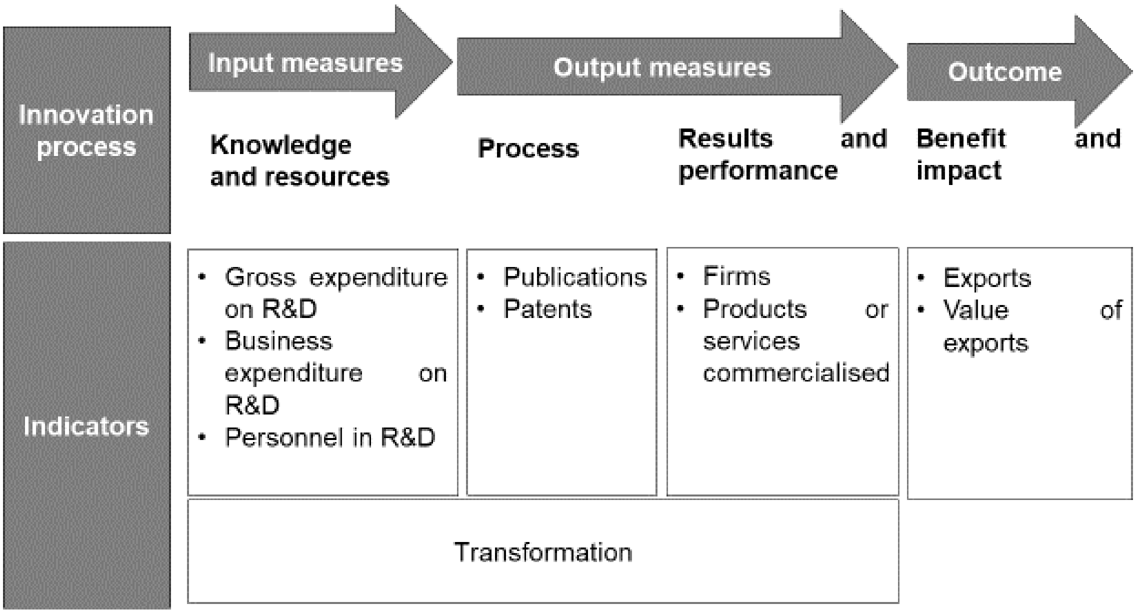


Figure 5: Potential innovation indicators for the bioeconomy in South Africa. (Source: own illustration adapted from Wydra (2020)).

3.3 SCIENTOMETRIC APPROACH

Scientometrics is the science of measuring and analysing science, technology and innovation quantitatively. Scientometrics methodologies have been widely used to measure science and technology, however, the use of scientometrics in measuring innovation is still challenging due to the nature of innovation as it cross-cuts science, technology and economic domains, and data is found in different databases and using different classifications (Leydesdorff, Rotolo and Rafols, 2012). Scientometrics studies on science and technology output indicators have mainly focused on scientific publications, citations, and patents. For example, Grilliches (1984), Jaffe et al. (1993), and Trajtenberg (1990b) among others, use patent citations as a tool to measure the dynamics of knowledge and innovation in the economy. Leydesdorff and Bornmann (2012) mapped patent data at the USPTO using overlays to generate Google Maps. Bambo and Pouris (2020) mapped bioeconomy research publications in South Africa using bibliometrics. An in-depth literature review on scientometric studies is provided in Chapter 2. In this study, bibliometrics and patentometrics are used to study the publications and patents trends for the bioeconomy in South Africa respectively. The study also employs a systematic literature review methodology to analyse scientific publications on innovation indicators published between 2014 and 2019. The rest of the data is collected from national experimental surveys, various websites and associations, and the OECD databases to analyse research expenditures, firms' outputs and exports values in the bioeconomy in South Africa. The research approaches and structures are summarised in the sections below.

3.3.1 Qualitative approach

The first part of the research (Fig. 6) consists of two work-streams, namely bibliometric analysis of bioeconomy indicators and a literature review of publications. The methodology is discussed in detail in Chapter 4. There are a number of publications documented with similar approaches. Pfau et al. (2014) based their methods and results of the literature selection on bioeconomy on practical screening criteria to identify different visions and the current understanding of the relationship between the bioeconomy and sustainability in scientific literature. Stegmann, Londo and Jungiger (2020) conducted a literature review on circular bioeconomy and analysed the role of the circular bioeconomy concept in north-west European bioeconomy clusters by means of interviews. Their finding was that the concept of circular bioeconomy contributes to improving the sustainability of the bioeconomy, however potential trade-offs need to be addressed, especially social issues and issues related to product use. Dziallas and Blind (2019) analysed scientific publications on innovation indicators published between 1980 and 2015 to identify innovation indicators throughout the innovation process. The authors found that more process indicators than product indicators exist in the literature.

The data on R&D expenditures in the bioeconomy can be sourced from statistical publications such as national surveys, however, data is generally classified by scientific field. Further, important sectors of the bioeconomy such as chemicals and pulp and paper are not 100% bio-based.

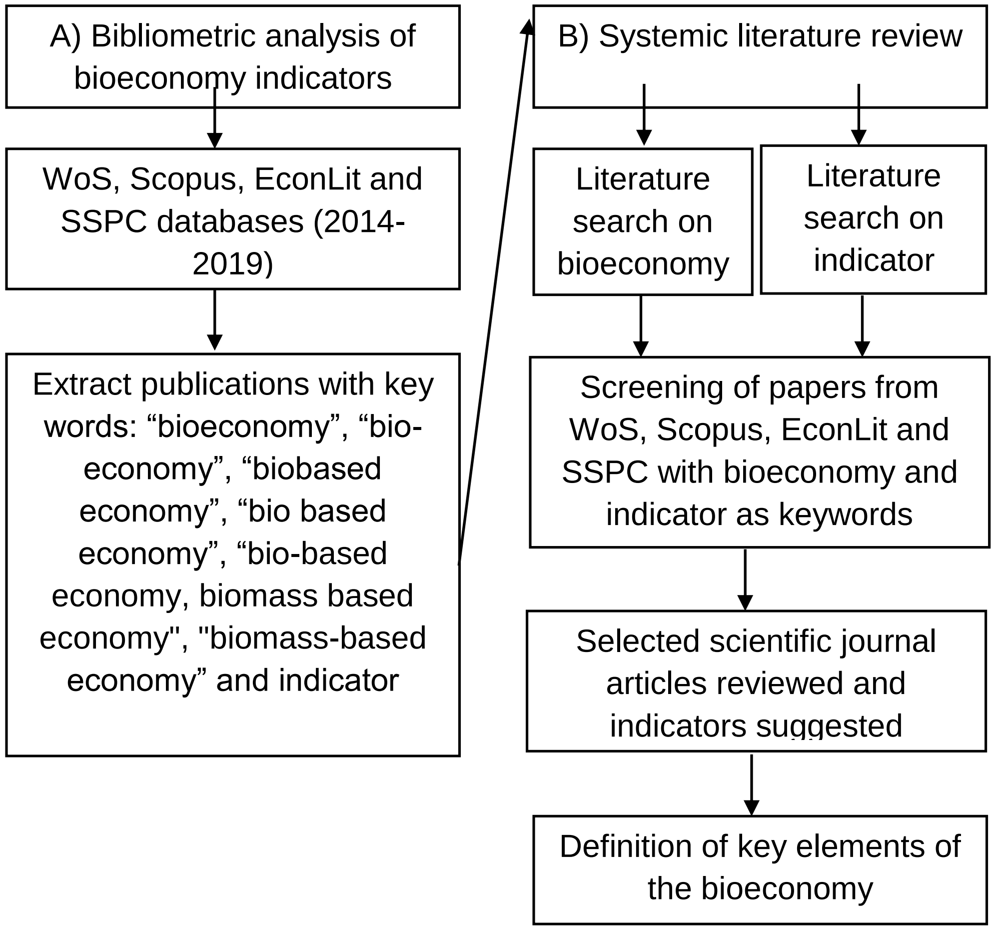


Figure 6: Qualitative research approach and structure for this study (Own illustration adapted from Stegmann et al. (2020))

Data from national accounts may therefore overestimate or underestimate the bioeconomy. The challenge is attributing the data from these sectors to the bioeconomy, i.e. the use of bio-based shares or providing estimates. This means that to get accurate data an innovation survey for the bioeconomy is required. The challenge may be that firms are not aware of the concept and statistical boundaries of the bioeconomy when providing the data for this purpose. The questionnaires for such a bioeconomy innovation survey must be precise and clear to eliminate errors.

3.3.2 Quantitative approach

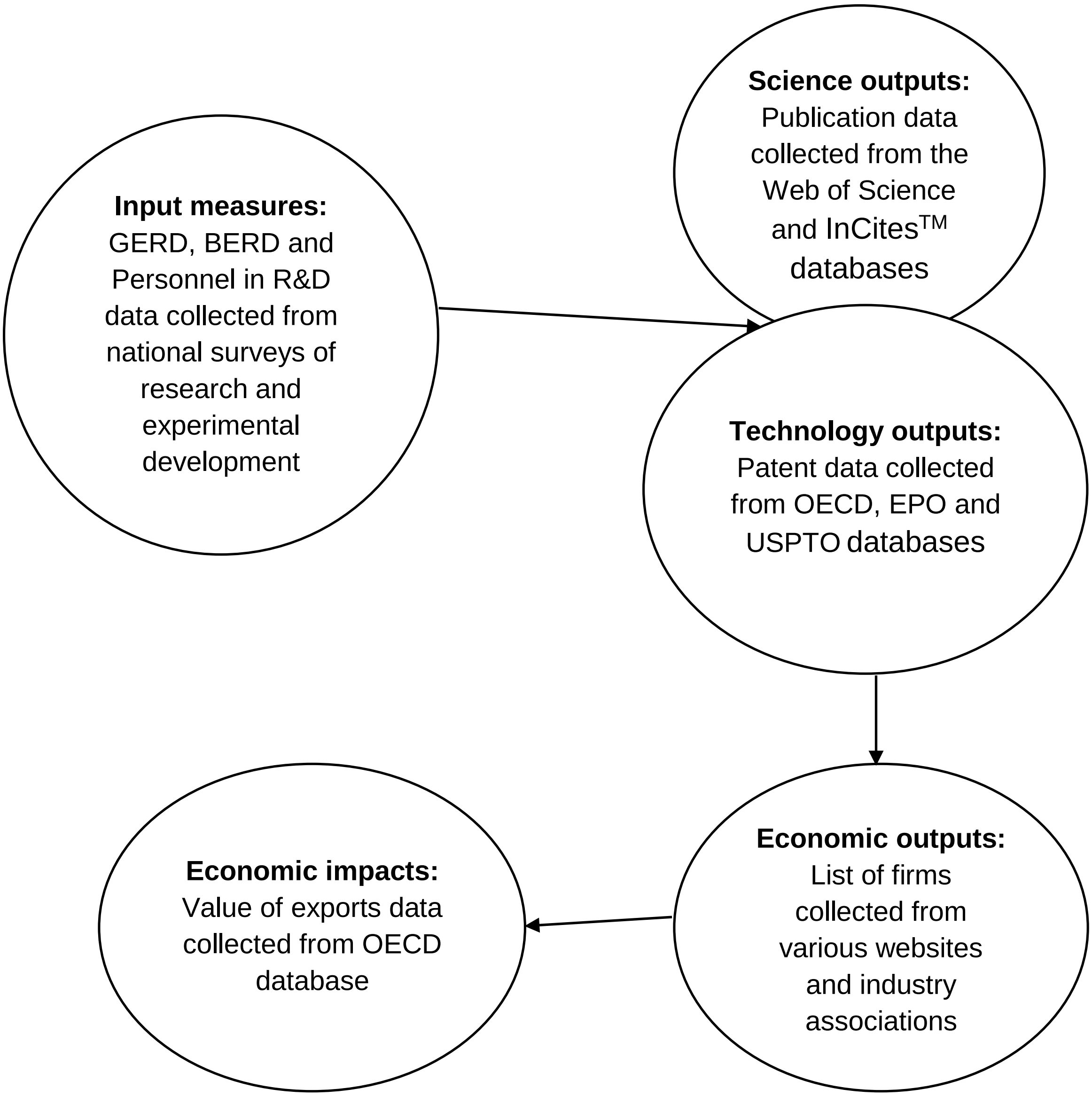


Figure 7: Quantitative research approach and structure and development of indicators for this study (Own illustration).

Analyses of scientific publications and patents and their citations provide information on the performance of the science, technology and innovation system over time and can be compared with other countries. To conduct bibliometric research, the WoS and InCites™ databases are used in this study. Patent data is collected from the OECD, EPO and USPTO databases. These databases are explained in detail in chapter 4.

The list of active bioeconomy firms is sourced from various websites and industry associations, however, to measure the output and impact of innovation at a firm level, an innovation survey is required. Data on the value of exports as a proxy for innovation at the firm level is sourced from the OECD database. Exports and innovation have been shown to correlate in various studies, as detailed in chapter 2. A summary of the conceptual approach is depicted in figure 7.

In conclusion, the proposed indicators in this study address all aspects of the innovation pipeline, taking into account the linear and the non-linear nature of the pipeline, as well as the links within the pipeline. Examples of linear and non-linear innovation pipelines proposed in this study are depicted above but there are others in existence. The research approaches – qualitative and quantitative – as discussed above, form the basis of the methodology for this study. The methodologies are presented and justified in Chapter 4.

CHAPTER 4: METHODOLOGY

The methods used for the study are presented and justified in this section. These are the bibliometric analysis of bioeconomy indicators and systemic review of literature (4.1), analyses of GERD and BERD in the bioeconomy in South Africa (4.2), analysis of the number of researchers performing R&D in the bioeconomy in South Africa (4.3), bibliometric analysis of bioeconomy research in South Africa (4.4), patentometric analysis of bioeconomy in South Africa (4.5), analysis of the number of active firms in the bioeconomy in South Africa (4.6) and analysis of export values in the bioeconomy in South Africa (4.7). The methodology for each of the sections are explained.

4.1 METHODOLOGY FOR BIBLIOMETRIC ANALYSIS OF BIOECONOMY INDICATORS AND SYSTEMATIC REVIEW OF LITERATURE

The bioeconomy is multidisciplinary and spans across many sectors, mainly the natural sciences, including the health sciences and agricultural sciences, industry and environmental sciences, economics and social sciences. A number of studies have been carried out using bibliometric data analysis techniques to present an overview of the growth of bioeconomy literature (Pfau et al., 2014; Bugge et al., 2016; Bambo and Pouris, 2020; Duquenne et al., 2020). The data for bibliometric analysis in this study was retrieved from the WoS, Scopus, EconLit and SSPC. Similar databases were previously used in bibliometric studies for the bioeconomy (Pfau et al., 2014; Bugge et al., 2016; Bambo and Pouris, 2020; Duquenne et al., 2020). WoS (previously known as Web of Knowledge) is an online subscription-based scientific citation indexing service, originally produced by the Institute for Scientific Information (ISI) and later maintained by Clarivate Analytics, that provides a comprehensive citation search. It gives access to multiple databases that reference cross-disciplinary research, which allows for in-depth exploration of specialised sub-fields within an academic or scientific discipline. It covers areas of science, social science, arts and humanities. Scopus is an abstract and citation database that covers almost 36,377 titles from about 11,678 publishers, of which

34,346 are peer-reviewed journals in the life sciences, social sciences, physical sciences and health sciences. EconLit, the American Economic Association's electronic database, is the world's foremost source of references to economic literature. The database contains more than 1.1 million records from 1886-present. EconLit covers virtually every area related to economics. SSPC searches across a range of ProQuest’s specialist indexes and full-text social sciences databases, covering subject areas including Politics, Sociology, Education, Linguistics and Criminal Justice. As the bioeconomy cross-cuts many sectors, the selected databases cover the broader sectors of the bioeconomy, that is the natural sciences, environmental sciences, agricultural sciences, social sciences, health sciences and economics. This may not be the full comprehensive list of sectors of the bioeconomy, but cover most of the field and the literature in general. For the bioeconomy search various synonyms were used, as suggested in the literature (Pfau et al., 2014; Bugge et al., 2016; Bambo and Pouris, 2020; Duquenne et al., 2020). These are: “bioeconomy”, “bio-economy”, “biobased economy”, “bio based economy”, “bio-based economy, biomass based economy", and "biomass-based economy”. For indicators search, the key word ‘indicator’ was used. For each search, a combination of all search terms was used, linking the bioeconomy and indicators search terms with AND.

For the literature review two main topics were identified for analysis: ‘bioeconomy’ and ‘indicators’. The study is focused on indicators for measuring the progress of the bioeconomy. The bioeconomy was therefore considered as a primary topic and indicators as a secondary topic. The aim of the literature review was to understand what publications perceive as important key indicators for the bioeconomy. The literature review was conducted by searching for the bioeconomy terms in the titles, keywords and abstracts (as suggested by Pfau et al., 2014), and for indicators in the full texts. The review consisted of a screening of papers from WoS, Scopus, EconLit and SSPC with ‘bioeconomy’ and ‘indicator’ as keywords as indicated above. After the screening of papers in these databases, selected scientific journal articles were reviewed on the suggested indicators to understand the literature in general. A list of the papers that were considered relevant to the analysis was drawn and comparisons done. A qualitative content analysis of the shortlisted articles was conducted to provide systematic answers to the commonly used indicators since

2014 in monitoring national bioeconomy strategies. The contents of these papers were summarised in a table form. For each database data was limited from 2014 to 2019, as most of the bioeconomy strategies were developed during this period.

4.2 METHODOLOGY FOR GERD AND BERD ANALYSES

The data on GERD and BERD between 2008/09 and 2017/18 in the bioeconomy was obtained from the 2017/18 South African National Survey of Research and Experimental Development (DSI, 2019). The term 'biotechnology' was used for data extraction, as R&D Survey data is organised by scientific field and not by economic sector. The expenditure on R&D is a key measure of resources devoted to R&D by public and private institutions.

4.3 METHODOLOGY FOR RESEARCHERS' ANALYSIS

The data on the number of researchers performing R&D in the bioeconomy was obtained from the HEMIS data provided by the DHET. The term 'biotechnology' was used for data extraction as researchers' data in bioeconomy is still organised by scientific field. Biotechnology is a common thread in most bioeconomy policies globally and is therefore a fair proxy.

4.4 METHODOLOGY FOR BIBLIOMETRIC ANALYSIS OF BIOECONOMY RESEARCH

The bibliometric analysis was used in this study to observe the growth of bioeconomy research in South Africa in terms of the number of South African authored publications and citations in peer reviewed international journals in bioeconomy, and in order to position the country's overall bioeconomy through the overall production of literature in an international context such as Brazil, Russia, China and India (BRICS) nations and other selected countries such as Egypt, Germany, Malaysia and United States of America. Bibliometric analysis is considered one of the most effective methods in assessing research performance, and for comparisons of different disciplines, collaboration profiles, comparisons of countries, changes over time and other outcomes which are not possible to assess through methods such as peer review. Bibliometrics analysis was performed on the data obtained from the WoS Core Collection database for publications and citations. The data for citations was exported to the InCites database for analysis. The WoS is an online subscription-based scientific citation indexing service, originally produced by the ISI and later maintained by Clarivate Analytics. The WoS provides a list of cited articles, each of which is accompanied by a list of citing articles (Garfield, 1964). The WoS is used for research dealing with a particular topic in widely diffused journals and for citation analyses. InCites is an analytical tool provided by Clarivate Analytics which uses the same underlying data from the WoS and is used to gather the total number of citations for each country by year.

The WoS Core Collection database was used for the search of publications from South Africa and compared with that from BRICS countries, Egypt, Germany, Malaysia and USA. A number of studies in bioeconomy and biotechnology research have conducted bibliometric analyses using the WoS (Sevukan and Sharma, 2008; Bajwa and Yaldram, 2013; Pfau et al., 2014; Bugge et al., 2016; Makhoba and Pouris, 2016; Bambo and Pouris, 2020; Duquenne et al., 2020). The analysis was limited to articles only, as the focus of the study is on scientific research outputs, and this approach is documented in other papers (Makhoba and Pouris, 2016). Data was limited to ten years, i.e. 2008 to 2018, as most bioeconomy strategies were developed during this period. Germany is among the first countries to develop a bioeconomy strategy in 2010 (BMBF and BMEL, 2015). This period is also important in South Africa as it falls under the ten-year innovation plan – towards a knowledge-based economy (DST, 2007a). Further, *Bioeconomy to 2030: designing policy agenda* was published in 2009 by the OECD (OECD, 2009a), signalling the beginning of a bioeconomy "era". The book provided guidance to countries' development of bioeconomy strategies and explores policy options to support the social, environmental and economic benefits of a bioeconomy. Therefore, it would not have added value in a bioeconomy context to go back further than 2008. The data search was conducted up to 2018. For citations, data analysis included all types of citation indexes (i.e. science, social science, humanities etc.) as bioeconomy cross-cuts many fields of sciences. This approach is documented by Pfau et al. (2014) as the authors used a multi-disciplinary approach for a bibliometric analysis of bioeconomy. To create a complete picture on the number of South African authored publications and citations in bioeconomy in peer reviewed international journals, both keywords 'bioeconomy' and 'biotechnology' were considered for the analysis as publication data is generally organised by scientific field and not by economic sector. Further, within the bioeconomy definition, biotechnology is a common thread and therefore its inclusion will cover most of the fields in the bioeconomy. The following keywords and their variants were selected as suggested in the literature (Sevukan and Sharma, 2008; Bajwa and Yaldram, 2013; Pfau et al., 2014; Bugge et al., 2016; Bambo and Pouris, 2020; Duquenne et al., 2020): bio* OR "bioeconomy" OR "bio-economy" OR “bio economy” OR biobased* OR “bio based*” OR “bio-based*” OR "biobased economy*" OR "bio based economy*" OR "bio-based economy*" OR "biomass based economy*" OR "biomass-based economy*" OR "biotechnology". In this case, a top down keyword search and Boolean operators were used. The search results were carried out with at least one South African resident as an author or co-author. The same strategy was used to collect data for selected countries, only by changing the name of the country of residence.

The InCites database was then used to gather the total number of citations for each country by year up to 2015. The years 2016, 2017 and 2018 were not considered for the total citations analysis to allow each of the three years to gather full citations. These citations were then totalled to create a measure of the quality of the scientific production for each country for the selected period.

A descriptive approach was used to identify the trends based on the publication data. The analysis focused on investigating countries with which South Africa collaborates the most on bioeconomy research, the most prolific research institutions in bioeconomy research in the country, the top journals selected by South African researchers, the subject categories (since bioeconomy is a multidisciplinary field), the percentage of publications in top 1% and top 10%, and the percentage of international and industry collaborations.

4.5 METHODOLOGY FOR PATENTOMETRIC ANALYSIS OF BIOECONOMY

Patentometric analysis was used to study the technological performance of South Africa in bioeconomy, as reflected by its patenting activities during 2008 to 2018, to compare South Africa's performance among the other BRICS countries. Patentometric analysis is commonly used in measuring technological innovation and country rankings.

To identify bioeconomy patents, the terms biotechnology, selected environment-related technologies, medical technology and pharmaceuticals from the OECD database were used to search for patents, as patents data is classified by technology and not by economic sector. Biotechnology is the common thread of bioeconomy policies globally (Aguilar, Twardowski and Wohlgemuth, 2019). The International Patent Classification (IPC) codes for biotechnology, as classified by the OECD (OECD, 2005:32), was used to identify biotechnology patents. The IPC codes for health-related patents, as classified by the OECD (OECD, 2009c:60), was used to identify pharmaceuticals and medical technologies patents. The IPC codes for environment-related technologies patents, as classified by the OECD (OECD, 2009d:52), was used to identify environment patents. The environment-related technologies patents were limited to biomass and waste to energy patents. There are a number of authors that use similar classes to search for biotechnology patents (Chen and Guan, 2011; Arts, Appio and Van Looy, 2013; Patra and Muchie, 2017; Makhoba and Pouris, 2019a) and health-related patents (Litchtenberg and Virabhak, 2002; Makhoba and Pouris, 2019a).

Patents were identified using the following codes of IPC:

- Biotechnology patents filed in IPC classes A01H1/00, A01H4/00, A61K38/00, A61K39/00, A61K48/00, C02F3/34, C07G (11/00, 13/00,15/00), C07K (4/00, 14/00, 16/00, 17/00, 19/00), C12M, C12N, C12P, C12Q, C12S, G01N27/327, G01N33/(53*,54*,55*,57*,68,74,76,78,88,92).

- Patents in pharmaceuticals filed in IPC class A61K, excluding A61K8/* (cosmetics).

- Medical technologies patents filed in IPC classes A61 [B,C,D,F,G,H,J,L,M,N] and H05G.

- Environment-related technologies patents filed in IPC classes C10L5/40-48 and F02B43/08.

Patent count data was based on fractional counts for patents with multiple inventors, inventors' country of residence and by priority date for biotechnology, selected environment-related technologies, medical technology and pharmaceuticals patents granted at the EPO and the USPTO, applications filed under the PCT, IP5 Patent families, and triadic patent families. The data was obtained from the OECD Statistics (OECD.Stat) (OECD, 2019a) using Patents by Technology Database. The OECD Statistics database enables users to search for, build own tables or figures and extract data from across OECD's databases. The search was conducted during the months of June to October 2019.

The most prolific organisations and the types of institutions for BRICS, Egypt and Nigeria were analysed for the period between 2008 to 2016. The data was limited to patents data retrieved from the EPO Patent Statistical Database (PATSTAT) and the USPTO Patent Full-Text and Image Database (PatFT) (version October 2019) for their high data quality. The search included at least one of the biotechnology, pharmaceuticals, medical technologies and environment-related technologies IPC classes with a priority date of 2008 to 2018 and the inventors' country of residence using the country's abbreviations (BR, RU, IN, CN, ZA, EG and NG) respectively. The search was conducted during the months of June to October 2019.

A number of similar studies have previously been conducted within the BRICS or selected African countries but using different databases from the ones used in this study or focusing on different periods of investigation and mainly limited to biotechnology. The study on patent citations within the BRICS or selected African countries is novel. In South Africa, a previous study on mapping of biotechnology patents was carried out using WIPO Patentscope database based on whole number count for period 2001 to 2014 (Patra and Muchie 2017; Makhoba and Pouris, 2019a). In China, Chen and Guan (2011) counted patents in biotechnology in the USPTO during 1995 to 2008. They employed bibliometrics and social network analysis techniques to measure the patent performance and knowledge relationship at organisational and regional levels respectively. Mallick et al. (2015) provided an overview on Indian patents on biotechnology using published papers as the source of data. They shared the patenting activities in biotechnology filed and granted at the Indian Patent Office, which shows the numbers to be inconsistent between the years of 2000 and 2014. The other sources of data of biotechnology patents among the BRICS is gathered through diverse secondary sources, for which the results are published by the OECD biotechnology Statistics (van Beuzekom and Arundel, 2009). The data in this study will contribute to the literature on patents in bioeconomy in South Africa and, specifically, the study addresses recommendations made by NACI on the data required to measure patents outputs at the EPO and USPTO for the Bioeconomy Strategy in South Africa.

Data for patents registered at the South African Patent Office (CIPC) was provided by the CIPC and limited to biotechnology. The CIPC publish granted patents on their website on a monthly basis, which can be retrieved through the CIPC Patent Search. There is, however, no online counting facility and thus counting is done manually and is time consuming. The counting at the CIPC was based on whole number count as data on fractional count is not readily available. A number of studies show that counting methods have minor or no effect on country rankings in patent counts (Zheng et al., 2014; Elango and Rajendran, 2017).

Patents in biotechnology, pharmaceuticals, medical technologies and environment-related technologies taken from the EPO PATSTAT and the USPTO PatFT were considered for citation analysis. The OECD provides Citations database ("OECD Citations database, July 2019") and Patent Quality Indicators database ("OECD Patent Quality Indicators database, July 2019") for patents registered at the EPO and the USPTO. The OECD's citations database provides international citations data that can be easily exploited and used for comparative analyses of flows of knowledge and innovation (Webb et al., 2005). The OECD Citations database provides information on patent and npl citations (or references) found in patent documents. Data covers citations made in patents filed at the EPO and the USPTO. The database covers all citations present in the EPO from 1978 onwards, and all citations made in the USPTO patent grants from 1976. The OECD Citation database mainly derives from the infrastructure proposed in Webb et al. (2005). The list of indicators from the OECD Citation database are defined and discussed in detail in the OECD working paper (Squicciarini et al., 2013). Once patents searches were completed, the number of citations were recorded by analysing each patent using the OECD Citation database, by searching and examining each patent (search conducted using patent number) manually using IBM SPSS Statistics 26 (DATA Editor) to record the number of backward, non-patent literature and forward citations. The forward citations from the OECD citation database are counted over a period of five or seven years (truncated) after the publication date, for both the EPO and the USPTO. The EPO further includes citation counts when only x and y citations are considered. The x and y citations are defined (Squicciarini et al., 2013). Counts also include self-citations as recommended by Hall, Jaffe and Trajtenberg (2005). The search was conducted in July 2019.

4.6 **METHODOLOGY FOR THE NUMBER OF FIRMS IN THE BIOECONOMY**

The list of active firms was collected from the DSI, the different industry associations and various websites as previously done by other researchers (Patra and Muchie, 2017) and national biotechnology surveys (DST 2003; 2007b). These are the DSI; NRF; TIA; CSIR; Bioeconomy SA Portal; the Innovation Bridge; HSRC (R&D Surveys); IPASA; SAMED; GBMSA; SABO; SANSOR; AfricaBio; the Registrar of the GMO's Act 15 of 1997 and the GMO amendment Act of 2006; and the Registrar of Plant Breeders' Rights Act 15 of 1976 and amendments; FSA; SEOBI; MDASA; SAPA; SAPIA; SASA; RMAA; PMASA; RPO; and CAIA. As with the 2007 SA Biotechnology Survey (DST, 2007b), universities and service organisations, including organisations involved in marketing and distribution, were excluded as they either do not meet the OCED definition of biotechnology firm or dedicated biotechnology firm (van Beuzekom and Arundel, 2009) or do not undertake any biotechnology activities. Research councils such as the ARC, CSIR, SAMRC and MINTEK were included during the counting. These organisations also belong in the business sector as they sell their outputs at an economic price (OECD, 2002: 55). The study covers active bioeconomy firms during the period 2018-2021.

4.7 METHODOLOGY FOR EXPORT VALUES IN THE BIOECONOMY

The data on export values to estimate innovation at the firm level was extracted from the OECD Main TiVA indicators database. The TiVA are indicators used to measure the sources of value added when producing goods and services for export and import. This approach is said to eliminate the double or multiple counting problem encountered in traditional trade statistics. Gross exports are in line with official national statistics for total exports and imports of goods and services, and are adjusted for re-exports and estimates for GDP (OECD, 2019b). The TiVA indicators are expressed in USD millions at current prices. The following search strategy (Table 1) was followed:

Table 1: List of industry sectors that are considered in this study and the search strategy used to extract the gross exports values

Sectors	Search strategy
ALL	DTOTAL: Total
Agriculture, forestry and fisheries	D01T03: Agriculture, forestry and fishing
Food products, beverages and tobacco	D10T12: Food products, beverages and tobacco
Chemicals and pharmaceuticals	D20T21: Chemicals and pharmaceutical products
Wood and paper products; printing	D16T18: Wood and paper products; printing

The bioeconomy industry sectors in South Africa mainly include agriculture, forestry, fisheries, food, paper and pulp, parts of chemicals and pharmaceuticals, biotechnological industries and parts of energy industries. For measurement purposes of the South African Bioeconomy Strategy, the NACI recommends the use of economic sectors in the bioeconomy as proposed by Haarich (2017:18). These are: (1) core bioeconomy sectors and relate to primary products, which are agriculture, forestry, fisheries and aquaculture, bio-energy and bio-fuels, food and beverages, feed industry and bio-based products and processes; (2) the partial bioeconomy sectors, which are sectors that use biological sources as input for their production processes – chemicals and plastics, construction, paper and pulp, pharmaceuticals, textiles, waste management and biotechnology; and (3) sectors that are indirectly impacted by the bioeconomy – technologies, machinery and equipment, services, water supply and wastewater treatment, energy and retail trade. Therefore, the proposed search strategy in this study may be omitting other industry sectors or over-measuring the size of the South African bioeconomy sector in terms of the TiVA indicators.

As articulated in this document already, the different sectors and subsectors composing the bioeconomy are not easily identifiable and remain a challenge (Wesseler and von Braun, 2017). From a methodological point of view, the main challenge for bioeconomy measurements is that important sectors for the bioeconomy, such as chemicals, textiles, rubbers and plastics and so on, are not 100% bio-based economic sectors. Therefore, information for sectors from national accounts are likely to have underestimated or overestimated figures for the bioeconomy. As a result, bio-based shares for sectors are estimated and used as a proxy to estimate the proportion of the bioeconomy in a certain sector (Ronzon and M'Barek, 2018; Ronzon et al., 2017; Piotrowski, Carus and Carrez, 2018). Thus the search strategy needs to be investigated further by measurement experts and subject matter experts with specific knowledge of value chains and economic sectors. The specification in South Africa can be extracted using the standard industrial classification (SIC) codes of economic development provided by Statistics South Africa. Nevertheless, the search strategy used in this study covers the majority of the sectors in the bioeconomy and is a fair proxy.

The seven methods deduced in this chapter to develop science, technology and innovation indicators for the bioeconomy address the key inputs and outputs measures for the bioeconomy. A comparison of the changes in inputs as compared to changes in output over time will allow an assessment of the efficiency of the bioeconomy innovation system. That means if outputs grow more rapidly than inputs, the efficiency is increasing. Chapter 5 will investigate how efficient is the bioeconomy innovation system in South Africa.

CHAPTER 5: RESULTS

This chapter addresses the research questions from the study: What are the bioeconomy indicators discussed in the literature in general? What are the bioeconomy GERD and BERD in South Africa? What is the number of R&D personnel in the bioeconomy in South Africa? What is the number of publications, patents and firms in the bioeconomy in South Africa? What is the value of exports in the bioeconomy in South Africa? These questions reflect key measures of inputs and outputs in the bioeconomy. The results lead to several observations and conclusions.

5.1 BIBLIOMETRIC ANALYSIS OF BIOECONOMY INDICATORS AND SYSTEMATIC REVIEW OF LITERATURE

5.1.1 Bibliographic Analysis

The search results revealed that the WoS, Scopus, EconLit and SSPC databases indexed 840, 532, 76 and 350 articles respectively (Fig. 8).

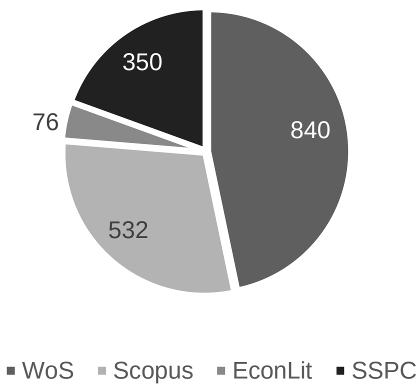


Figure 8: Share of number of publications on bioeconomy between WoS, Scopus, EcoLit and SSPC databases

Table 2: Top 9 Journals producing most articles from the selected databases, 2014 to 2019

WoS	% share	EconLit	% share	SSPC	% share	Scopus	% share
Journal of Cleaner Production (63)	7.5	Bio-based and applied economics (5)	6.6	Amfiteatru Economic (28)	8	Journal of Cleaner Production (33)	6.2
Sustainability (48)	5.7	Agbioforum (4)	5.3	BioSocieties (25)	7.1	Sustainability Switzerland (28)	5.3
New Biotechnology (32)	3.8	Technology analysis and strategic management (4)	5.3	Ambio (13)	3.7	European Biomass Conference and Exhibition Proceedings (21)	3.9
Biofuels Bioproducts Biorefining Biofpr (31)	3.7	Ecological economics (3)	3.9	Land Use Policy (11)	3.1	Biofuels Bioproducts and Biorefining (13)	2.4
Scandinavian Journal of Forest Research (24)	2.9	German journal of agricultural economics (3)	3.9	New Genetics and Society (9)	2.6	New Biotechnology (11)	2.1

Amfiteatru Economic (22)	2.6	New medit: mediterranean journal of economics, agriculture and environment (3)	3.9	Clean Technologies and Environmental Policy (8)	2.3	ACS Sustainable Chemistry and Engineering (7)	1.3
Bioresource Technology (14)	1.7	Applied economics (2)	2.6	Forest Policy and Economics (8)	2.3	Biomass and Bioenergy (7)	1.3
Biomass Bioenergy (13)	1.5	Ekonomika apk (2)	2.6	Cultural Studies of Science Education (7)	2	Bioresource Technology (7)	1.3
Biotechnology for Biofuels (13)	1.5	Energy policy (2)	2.6	Agriculture and Human Values (5)	1.4	Amfiteatru Economic (6)	1.1

Table 2 shows the top 9 journals producing the most articles from the selected databases respectively. Majority of the articles were from *Journal of Cleaner Production* and appeared in WoS (63) and Scopus (33) databases. Other journals that appeared in WoS and Scopus databases were *Sustainability*, *Biofuels Bioproducts and Biorefining*, *New Biotechnology*, *Bioresource Technology*, *Biomass and Bioenergy* and *Amfiteatru Economic*. *Amfiteatru Economic* also appeared in SSPC database. The journal *Sustainability* had second most articles from WoS (48) and Scopus (28) databases.

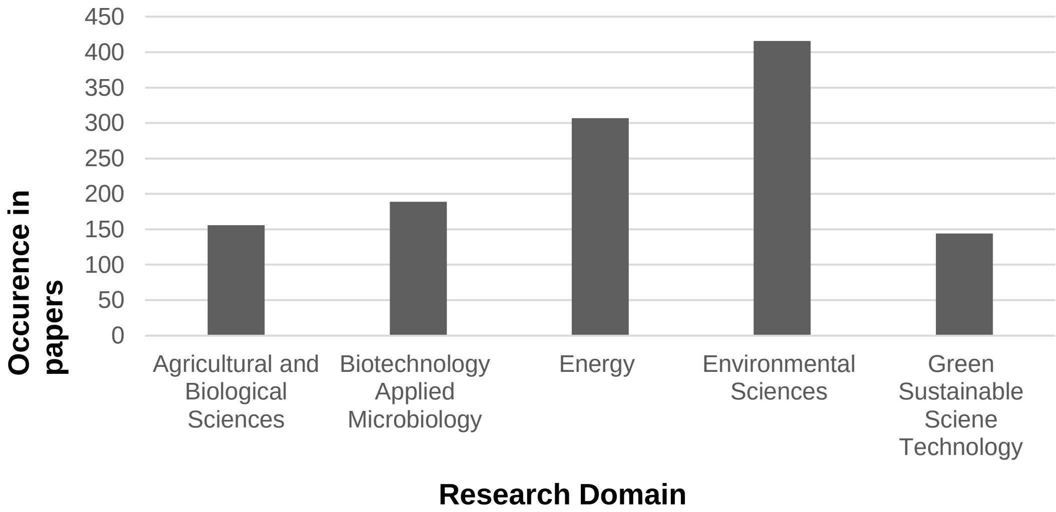


Figure 9: Classification according to research domains and their occurrence, for journals with 100 or more publications. Where journals with 100 or more publications appear in 1 or more databases, the total is provided.

Figure 9 shows the research domains regarding the bioeconomy for selected databases. Research domains under WoS on bioeconomy broadly focused on biotechnology and applied microbiology, environmental sciences, energy, business, agriculture and social sciences. The Scopus domains on bioeconomy broadly focused on environmental science, energy, agricultural and biological sciences. The EconLit domains on the bioeconomy broadly concerned alternative energy, agriculture, economics, marketing, business and the environment, while the SSPC domains were more on sustainable development and sustainability, innovations, biotechnology, biomass, climate change, economics, environmental impact and forests. Five research domains from the four databases were identified with over 100 published papers on the bioeconomy topic. The majority of the publications were on environment and related sciences: Environmental Sciences (416), Energy (307), Biotechnology Applied Microbiology (189), Agricultural and Biological Sciences (156) and Green Sustainable Science Technology (144).

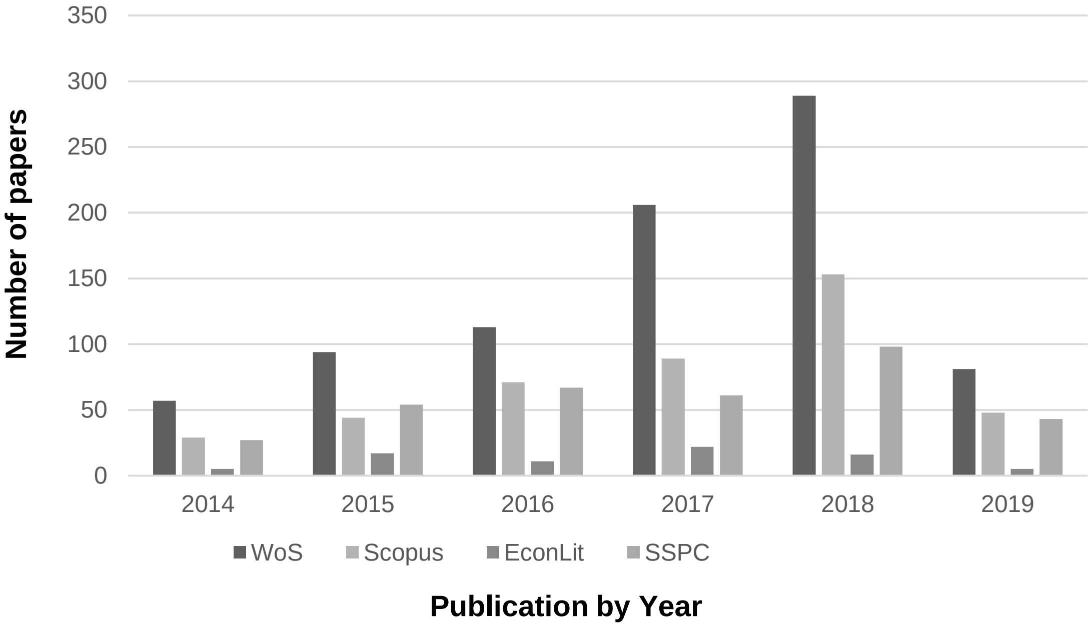


Figure 10: Total publication by year, 2014-2019.

Figure 10 shows the spread of the papers over time, presenting the number of papers published per year. Generally, publications are increasing annually, the highest being from WoS with over 57 papers published annually. Since the papers were selected in April 2019 the total for the year 2019 is not complete, however, the results as of April 2019 suggest a positive number of publications from most of the databases selected.

5.1.2 Indicators and the bioeconomy

Following the search on selected databases for papers with 'bioeconomy' and 'indicators' key search, Scopus produced 83 papers, SSPC produced 86 papers, WoS produced 37 papers and EconLit produced 3 papers (Fig. 11). Forty-five papers were chosen for review after a search of bioeconomy indicators in-text. The papers selected for review mentioned bioeconomy in titles, abstracts or keywords and indicators in body text. The main inclusion criterion, however, was that papers had to include a discussion of indicators for the bioeconomy. Table 3 list articles selected for review. A total of 31 articles from Scopus, 9 articles from WoS, 8 articles from SSPC and 1 article from EconLit were determined to be relevant for review (Table 4).

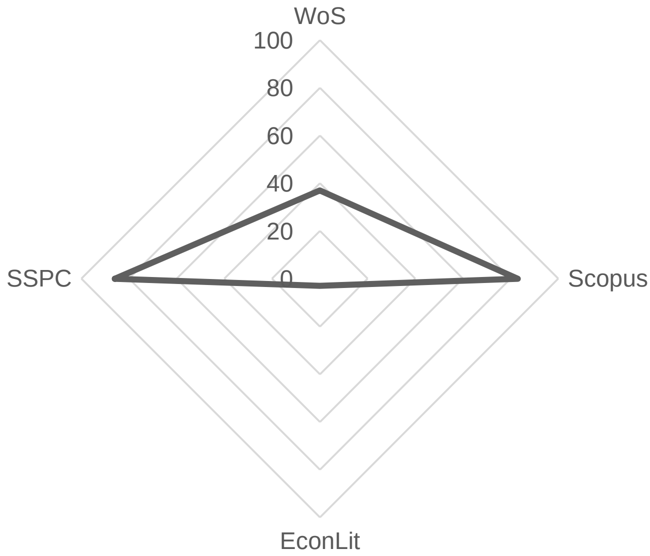


Figure 11: Number of bioeconomy publications when key word indicator was used

Table 3: Summary of literature on proposed bioeconomy indicators in alphabetical order

Reference	Journal	Database
Anghel et al.	Amfiteatru Economic	SSPC
Asanda and Stern	Ecological Economics	Scopus
Bartolini et al.	Energy Policy	Scopus
Bejinaru et al.	Amfiteatru Economic	SSPC
Biber-Freudenberger et al.	Sustainability	Scopus
Blanc et al.	Sustainability	Scopus
Bracco et al.	Sustainability	WoS and Scopus
Budzinski et al.	Cleaner Production	Scopus
Busu and Busu	Amfiteatru Economic	SSPC
Cîrstea et al.	Amfiteatru Economic	Scopus and SSPC
Cristóbal et al.	Biomass and Bioenergy	Scopus
Dehdarirad et al.	FEMS Microbiology Letters	Scopus
Djordjevic et al.	Amfiteatru Economic	SSPC
Efken et al.	NJAS-Wageningen Journal of Life Sciences	Scopus
Egenolf and Bringezu	Sustainability	WoS
Falcone and Imbert	Sustainability	WoS
Falcone et al.	Corporate Social Responsibility and Environmental Management	Scopus
Fritsche and Iriarte	Energies	WoS and Scopus
Hansen et al.	Sustainability	Scopus
Jander and Grundmann	Cleaner Production	Scopus
Karvonen et al.	Forest Ecosystems	WoS

Kuznecova et al.	Energy Procedia	Scopus
Laibach et al.	Technology in Society	Scopus
Lainez et al.	New Biotechnology	Scopus
Lindqvist et al.	Sustainability	Scopus
Majore et al.	Procedia Computer Science	Scopus
Martin et al.	Sustainability	WoS and Scopus
Mouysset et al.	Land Use Policy	Scopus
Muizniece et al. (1)	Environmental Climate Technologies	Scopus
Muizniece et al. (2)	Environmental Climate Technologies	Scopus
Nedelea et al.	Amfiteatru Economic	SSPC
O'Brien et al.	Land Use Policy	Scopus and SSPC
Paşnicu et al.	Amfiteatru Economic	SSPC
Philippidis and Sanjuán-López	Sustainability	Scopus
Pieratti et al.	Annals of Forest Research	Scopus
Rafiaani et al.	Renewable and Sustainable Energy Reviews	Scopus
Ronzon and M'Barek	Sustainability	WoS
Scarlat et al.	Environmental Development	Scopus
Sheldon	ACS Sustainable Chemistry and Engineering	Scopus
Siebert et al.	Cleaner Production	Scopus
Spierling et al.	Cleaner Production	Scopus
Talavyria et al.	Ekohomika	EconLit
Van Schoubroeck et al.	Renewable and Sustainable Energy Reviews	Scopus

Wen et al.	Sustainability	WoS
Zeug et al.	Sustainability	WoS

Table 4: Summary of bioeconomy indicators from selected literature

Category	Indicator	Description	Source
Economic	Economic growth, employment and investments	These are shares of Gross Domestic Product (GDP), Gross and/or local value added (G/LVA), turnover/sales and trade-offs. Employment, resource use, public-private investment, economic viability of products and processes, value added, value chains, innovation and competitiveness, clusters, market share, cost-benefit analysis, availability of funding, infrastructure, financial performance, firms Net Present Value, annualised cost and payback period, development level index, industrial culture, collaboration across industries, and innovation and macroeconomics trends.	(Scarlat et al., 2015; Budzinski et al., 2017; Anghel et al., 2018; Bartolini et al., 2017; Cîrstea et al., 2019; Efken et al., 2016; Karvonen et al., 2017; O'Brien et al., 2017; Asanda and Stern 2018; Bracco et al., 2018; Lainez et al., 2018; Nedelea et al., 2018; Philippidis and Sanjuán-López, 2018; Ronzon and M'Barek, 2018; Sheldon, 2018; Paşnicu et al., 2019; Talavyria et al., 2017; Laibach et al., 2019; Mouysset et al., 2019; Muizniece et al., 2019a; Wen et al., 2019).
Social	Sustainability	These are global implications such as hunger and poverty, job creation, quality of life, adequate remuneration, adequate working time, workers conditions and participation, inequalities, food security, access to water, sustainable consumer consumption, natural	(Budzinski et al., 2017; Bartolini et al., 2017; Karvonen et al., 2017; O'Brien et al., 2017; Siebert et al.,2017; Bracco et al., 2018; Martin et al., 2018; Rafiaani et al., 2018; Spierling et al., 2018;

		resources, health, rural development and climate change.	Paşnicu et al., 2019; Zeug et al., 2019).
	Society	End users' health and safety measures/ vulnerability to infectious disease, local community engagement, public opinion, feedback mechanisms, transparency, human capital, intellectual capital, knowledge capital development, relation capital, employee motivation, market share and employee satisfaction. end-of-life responsibility/life expectancy, consumer demand and skilled labour force, quality of academic institutions, smooth regulation processes, life cycle assessment and public acceptance of bioeconomy products.	(Siebert et al., 2017; Talavyria et al., 2017; Anghel et al., 2018; Bejinaru et al., 2018; Djordjevic et al., 2018; Falcone and Imbert, 2018; Martin et al., 2018; Nedelea et al., 2018; Sheldon, 2018; Van Schoubroeck et al., 2018; Blanc et al., 2019; Dehdarirad et al., 2019; Falcone et al., 2019).
Environment	Sustainability	Land and water availability, farmland allocation, impacts on sustainability and biodiversity, air quality, soil quality, ecological/environmental footprints and mapping of value chains.	(Majore et al., 2015; Cristóbal et al., 2016; Bartolini et al., 2017; O'Brien et al., 2017; Biber-Freudenberger et al., 2018; Martin et al., 2018; Spierling et al., 2018; Egenolf and Bringezu, 2019; Laibach et al., 2019; Lindqvist et al., 2019; Mouysset et al., 2019; Muizniece et al., 2019a).

	Biobased products, climate change mitigation, clean energy and natural resource management	Reduction in dependency on chemical-based products, reduction in greenhouse gas emissions such as carbon dioxide, reduction in dependency on fossil fuels and promotion of renewable and cleaner energy technologies. Availability and share of biomass. Substitution share indicator. Sustainability of water, soil and biodiversity improvements.	(Fritsche and Iriarte, 2014; Hansen et al., 2016; Budzinski et al., 2017; Talavyria et al., 2017; Busu and Busu, 2018; Kuznecova et al., 2018; Lainez et al., 2018; Nedelea et al., 2018; Van Schoubroeck et al., 2018; Cîrstea et al., 2019; Jander and Grundmann, 2019; Pieratti et al., 2019; Wen et al., 2019; Zeug et al., 2019).
Knowledge/ Innovation		Patents, publications, biotechnological efficiency and competitiveness.	(Biber-Freudenberger et al., 2018; Nedelea et al., 2018; Laibach et al., 2019; Muizniece et al., 2019b).

5.2 GERD AND BERD IN THE BIOECONOMY IN SOUTH AFRICA

Table 5: GERD in biotechnology and in total research fields in South Africa

Year	Biotechnology	Total
	R'000	R'000
2008/09	801 640	21 041 046
2009/10	917 917	20 954 677
2010/11	1 142 337	20 253 805
2011/12	1 065 286	22 209 192
2012/13	1 179 478	23 871 219
2013/14	1 266 325	25 660 573
2014/15	1 576 727	29 344 977
2015/16	1 843 363	32 336 679
2016/17	1 788 728	35 692 973
2017/18	1 797 013	38 724 590

Source: (DSI, 2019:8)

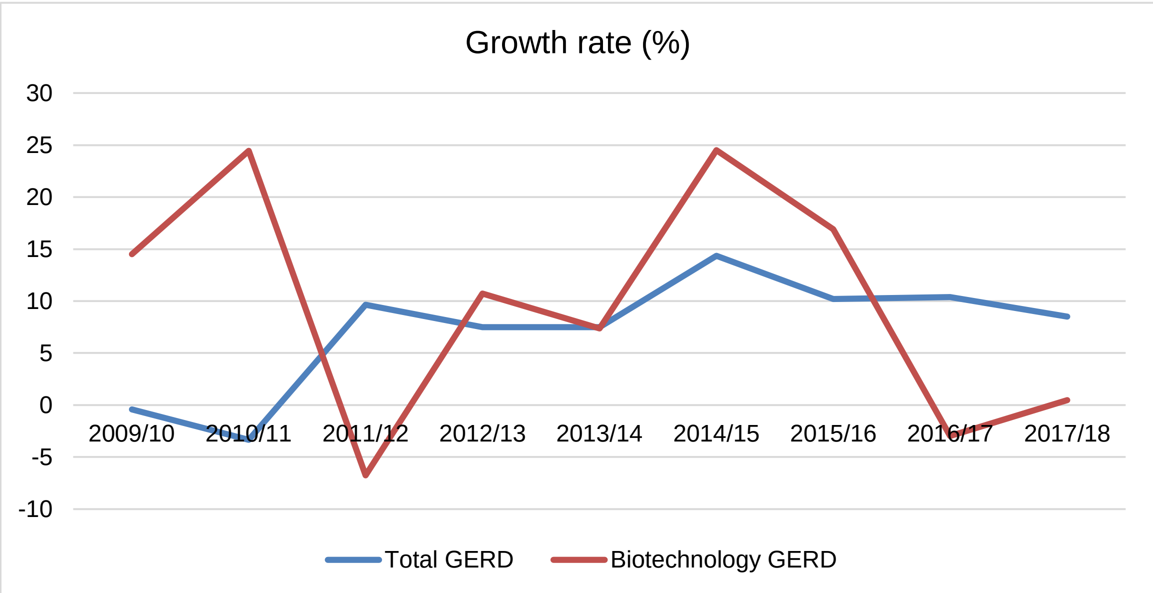


Figure 12: Biotechnology GERD trends in comparison to total GERD trends in South Africa

The GERD in biotechnology and in the total of research fields in South Africa is provided in Rand (Table 5). The results show an inconsistent growth rate (Fig. 12) in terms of the biotechnology GERD trends in comparison to total GERD trends in South Africa. For example, during the global economic recession that began in 2008/09, GERD in biotechnology in South Africa experienced a decline in growth rate to -6.74% in 2011/12. During 2013/14 and 2014/15, the growth rates had risen to 7.36% and 24.5% respectively. However, by 2015/16, the growth rate had declined to -2.96%. In contrast, the GERD for the total research growth rate was the lowest (-3.34) in 2010/11, but has been on a consistent rise since, with a growth rate of 10.38% in 2016/17. These observations appear to be similar in terms of BERD in biotechnology and in the total research fields in South Africa (Table 6 and Fig. 13).

Table 6: BERD in biotechnology and in total research fields in South Africa

Year	Biotechnology	Total
	R'000	R'000
2008/09	268923	12332012
2009/10	330232	11139237
2010/11	341695	10059010
2011/12	422121	10464022
2012/13	499589	10570726
2013/14	556275	11782848
2014/15	578747	13290951
2015/16	729299	13814995
2016/17	685170	14781270
2017/18	721698	15859185

Source: (DSI, 2019: 22)

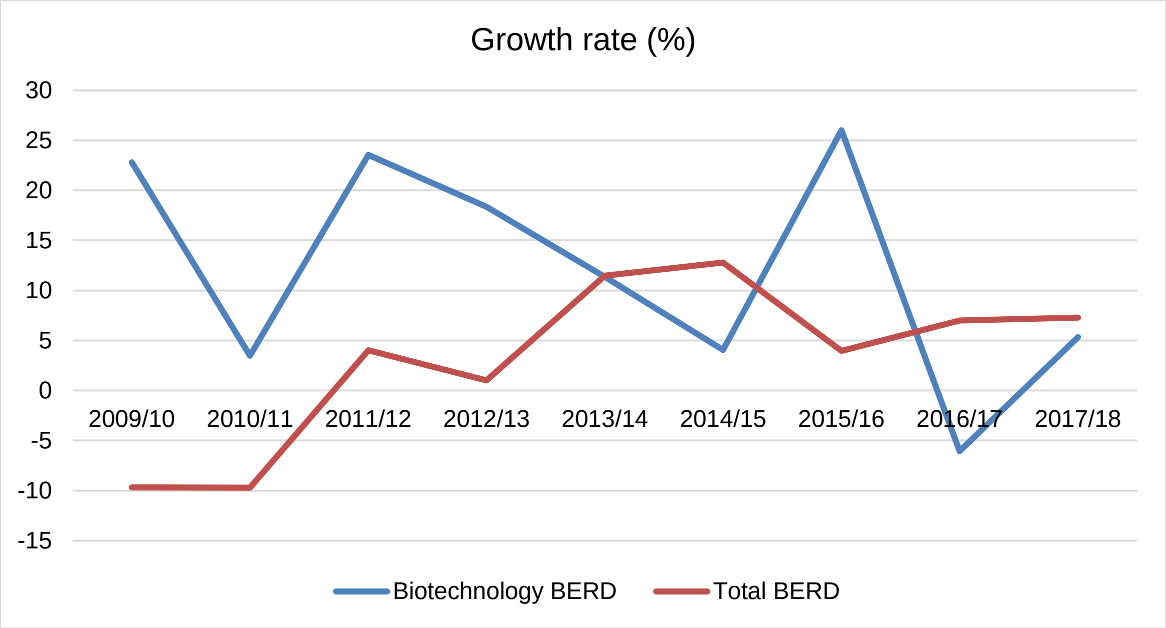


Figure 13: Biotechnology BERD trends in comparison to total BERD trends in South Africa.

For example, the growth rates for biotechnology BERD in South Africa was at 3.47% in 2010/11, reached its highest in 2015/16 at 26% and experienced the steepest decline in 2016/17 with a growth rate of -6,05%. In contrast, the BERD for total research growth rate was the lowest at -9.70 in 2009/10 and 2010/11, but experienced a consistent increase since with a growth rate of 7.29% in 2017/18.

5.3 THE NUMBER OF RESEARCHERS IN THE BIOECONOMY IN SOUTH AFRICA

The researchers in headcounts are provided in Table 7 and the growth rates in Figure 14. The number of biotechnology researchers started to pick up in 2015 and recorded the highest number in 2017 at 168 and a growth rate of 33.9% between 2015 and 2016.

Table 7: Researchers headcounts in biotechnology and total researchers in South Africa

year	Biotechnology researchers	Total researchers
2010	152	28 154
2011	127	30 993
2012	141	32 955
2013	134	36 133
2014	128	38 381
2015	123	41 639
2016	139	46 028
2017	168	50 549

Data provided is limited to the higher education sector. The majority of R&D personnel in South Africa are affiliated to the higher education sector (DSI, 2019:19). The data on biotechnology as per CESM excludes 'viticulture and grapevine biotechnology' or 'oenology and wine biotechnology' as they are counted separately. From the South African National Survey of Research and Experimental Development, "headcounts include non-SA R&D personnel (from 2016/17). Non-SA personnel are classified as those that are not from South Africa but are undertaking research in South Africa for a period exceeding six months. They can be temporary or permanent residents as described by the SNA" (DSI, 2019: 19). The headcount of research personnel is the total number of individuals engaged in the conception or creation of new knowledge.

In terms of total researchers in South Africa for all fields, the numbers have been near consistent with little growth rates recorded. For example, the growth rate for total researchers in South Africa in all fields was 10% in 2015 and slightly dropped to 9.83% in 2017.

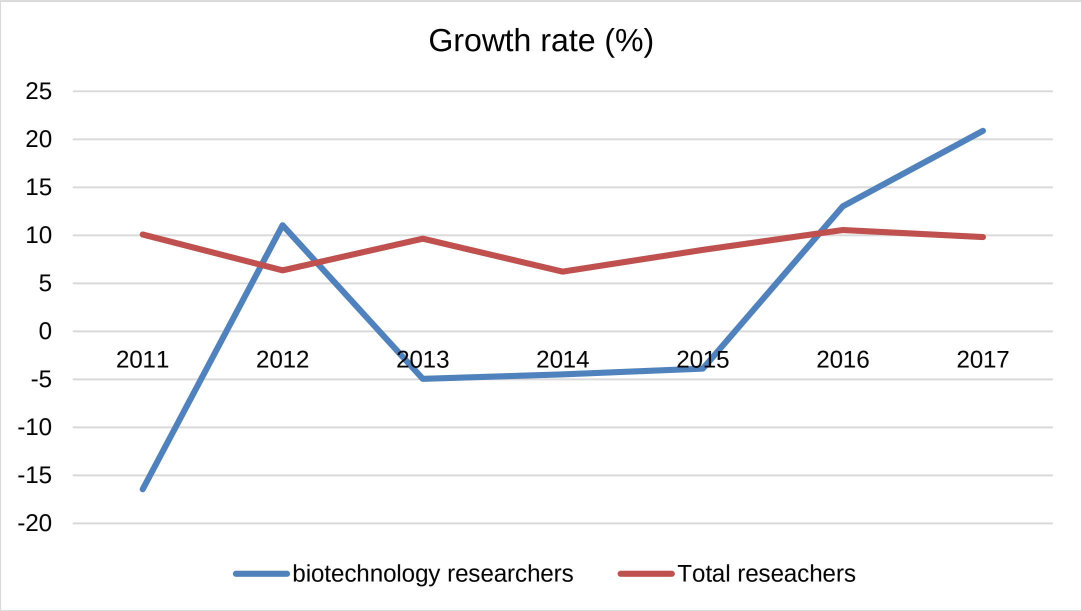


Figure 14: Biotechnology researchers' trends in comparison to total researchers' trends in South Africa

5.4 **BIBLIOMETRIC ANALYSIS OF BIOECONOMY IN SOUTH AFRICA**

Analysis of the WoS database identified 19040 publications in bioeconomy disciplines with at least one South African author for the period 2008-2018 (Table 8). The number of South African bioeconomy publications has shown a rising trend for this period, however the growth rate is varying, with an average of 11.3% (Fig. 15). The number of publications were low in 2012 and highest in 2015. It is noteworthy that South Africa launched the Biotechnology Strategy in 2001 (DST, 2001) and the Bioeconomy Strategy in 2014 (DST, 2013). The launch of the Biotechnology Strategy was accompanied by government financial support, however, the 2014 launch of the Bioeconomy Strategy did not attract much additional funding from government. The number of South African publications in general has shown a rising trend for the same period (Fig. 16). The findings are similar to that of Kahn (2011) who found that the number of South African journals indexed to the WoS increased in recent years, which may have contributed to increase in South African authored publications.

The New Funding Framework (NFF) for higher education institutions in South Africa introduced in 2003 also positively affected the number of publications in South

Africa (Pouris, 2012). The increase in scientific publications in South Africa is further attributed to the increase in international research collaborations (NACI, 2018). The citations trend for bioeconomy research with at least one South African author for the same period shows an inconsistent growth rate, with the period 2009 to 2010 and 2012 to 2013 displaying the highest growth rates. The total citations for South African research publications in general has shown a rising trend between 2008 to 2012, but has been on a decline post 2013 (Fig. 16). The citations trend for bioeconomy research with at least one South African seems higher than the total citations for South African research publications during the same period.

Table 8: South Africa bioeconomy research publications and citations by year, 2008-2018

Year	Total number of publications	Growth rate (%)	Total citations	Growth rate (%)
2008	893		27163	
2009	1002	12.2	26370	-2.92
2010	1171	16.9	34275	29.9
2011	1359	16.1	36831	7.46
2012	1405	3.38	26919	-26.9
2013	1666	18.6	33271	23.6
2014	1809	8.58	30068	-9.63
2015	2133	17.9	28997	-3.56
2016	2462	15.4	21948	-24.3
2017	2568	4.31	13344	-39.2
2018	2572	0.16	5667	

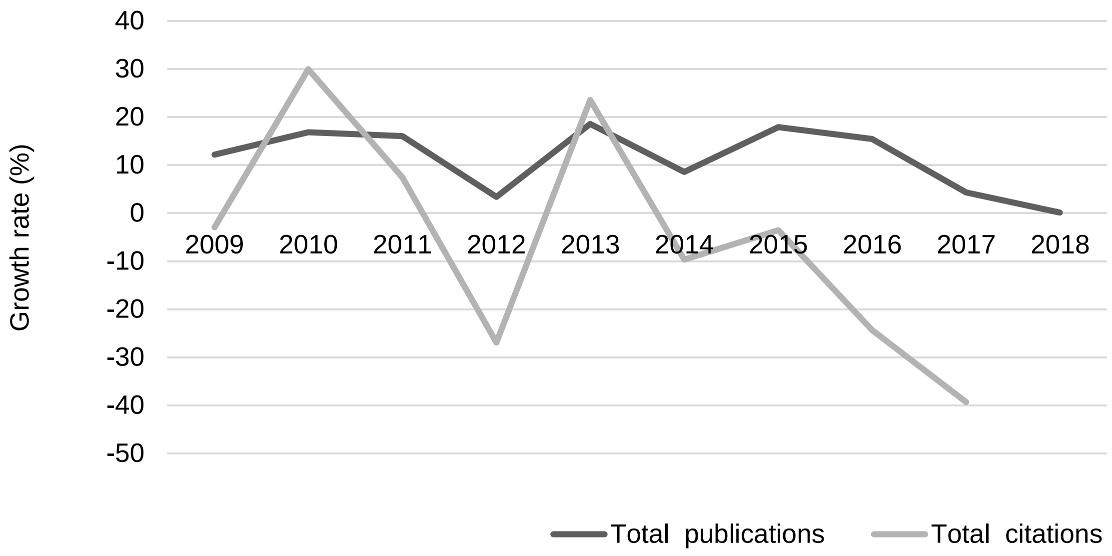


Figure 15: The publication and citation growth for bioeconomy in South Africa from 2009 to 2018.

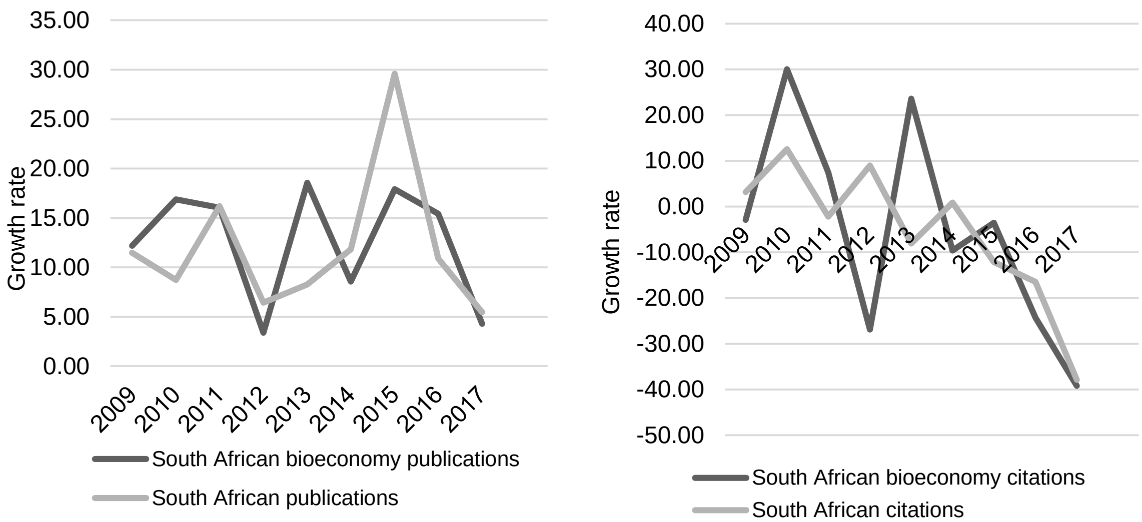


Figure 16: South African bioeconomy research publications and citations growth rates in comparison to South African total research publications and citations, 2009 to 2017

Table 9: South Africa total bioeconomy publications, 2008-2018

Year	Percentage documents cited	Percentage international collaborations	Percentage industry collaborations	Percentage documents in top 1%	Percentage documents in top 10%
2008	97.20	48.15	1.46	1.57	12.65
2009	97.01	51.10	1.60	1.20	9.580
2010	94.71	48.42	1.28	1.62	12.21
2011	96.17	52.06	1.18	2.58	12.67
2012	95.73	51.53	1.14	1.35	11.03
2013	94.48	55.13	1.56	2.16	13.92
2014	94.19	55.67	1.16	1.55	12.84
2015	91.97	56.84	1.30	2.74	13.52
2016	87.99	57.87	1.38	1.73	11.88
2017	81.91	60.08	0.87	1.58	11.66
2018	57.93	63.63	1.18	2.15	11.48

Pouris (2006) conducted a citation analysis of South African scientific disciplines from six universities and concluded that the country has citation foot-prints in only nine of the 22 broad scientific disciplines. All the nine scientific disciplines are covered in the bioeconomy sector. This could explain the higher citation growth rates for bioeconomy in South Africa in comparison to the total citations for South African research publications during the same period. In South Africa the health-related scientific publications are responsible for the largest single contribution from South African authors as indexed in Thomson Reuters ISI system (ASSAf, 2009), now the WoS.

On average (Table 9), 90% of South Africa bioeconomy publications were cited up to 2018, however, the appropriate duration for citation time in order to provide reliable citation data is at least three years (Abramo, D' Angelo and Cicero, 2012). The average citations up to the year 2015 is at 95%. About 55% of bioeconomy publications with at least one South African author were written in collaboration with researchers from other countries. The observation is slightly equivalent to the national percentage on international collaborations between 2007 and 2016, which is at 53% (NACI, 2018). Kahn (2011) found that the collaboration profile of South African scientific publications with foreign co-authors increased during the periods of 1990 to 1994 and 2004 to 2008 , and suggested that "it is this factor that best accounts for the rise in number of scientific publications by South Africans". The average percentage industry collaboration, publications in top 1% and publications in top 10% for South African bioeconomy publications is at 1.3%, 1.8% and 12.1% respectively. This is on par with the national average of 1.4% for both industry collaboration and publications in top 1%, but slightly higher than the national average publications in top 10%, which is at 9.8% for the period of 2007 to 2016. In South Africa, the percentage of international collaborations for bioeconomy publications increased from 48.15% in 2008 to 57.87% in 2016, which is slightly higher than the national total scientific publications percentage of international collaborations which increased from 40.46% in 2008 to 52.82% in 2018 (NACI, 2018).

Table 10: Number of South Africa bioeconomy publications in comparison with selected countries in alphabetical order, 2008-2018

Countries	Bioeconomy publications	World share (%)	World ranking
Brazil	90863	3.95	11
China	371952	16.2	02
Egypt	20928	0.91	28
Germany	164982	7.17	03
India	117394	5.10	05
Malaysia	19042	0.83	34
Russia	32648	1.42	22
South Africa	19040	0.83	33
USA	609403	26.5	1
World	2300174	100	

Among the BRICS countries (Table 10), China had the most publications, followed by India, Brazil, Russia and then South Africa. This observation is similar to the OECD (2016) compendium of bibliometric science indicators which reported a five-fold increase in publications from China, for the period of 2003 to 2012. South Africa, Malaysia and Egypt had an almost equivalent number of publications, that is 19040, 19042 and 20928 respectively. South Africa and Malaysia did not differ in terms of world share (0.83%). South Africa ranked 33 in the world in terms of the number of bioeconomy publications.

Table 11: Bioeconomy publications by year for world total and Brazil, Russia, India and China (BRICS)

Year	World	Growth rate (%)	Brazil	Growth rate (%)	Russia	Growth rate (%)	India	Growth rate (%)	China	Growth rate (%)
2008	131707		4407		1631		5082		11442	
2009	146697	11.4	5069	15.0	1805	10.7	5598	10.2	14442	26.2
2010	161985	10.4	5716	12.8	1960	8.59	6712	19.9	17061	18.1
2011	177665	9.68	6476	13.3	2009	2.50	7641	13.8	20804	21.9
2012	189372	6.59	7106	9.73	2025	0.80	8559	12.0	25297	21.6
2013	203492	7.46	7784	9.54	2171	7.21	9640	12.6	31289	23.7
2014	217103	6.69	8416	8.12	2548	17.4	10769	11.7	37398	19.5
2015	246165	13.4	9965	18.4	3656	43.5	14286	32.7	43582	16.5
2016	262449	6.62	10917	9.55	4298	17.6	15578	9.04	49867	14.4
2017	275633	5.02	12208	11.8	4974	15.7	16508	5.97	56244	12.8
2018	287906	4.45	12799	4.84	5571	12.0	17021	3.11	64526	14.7

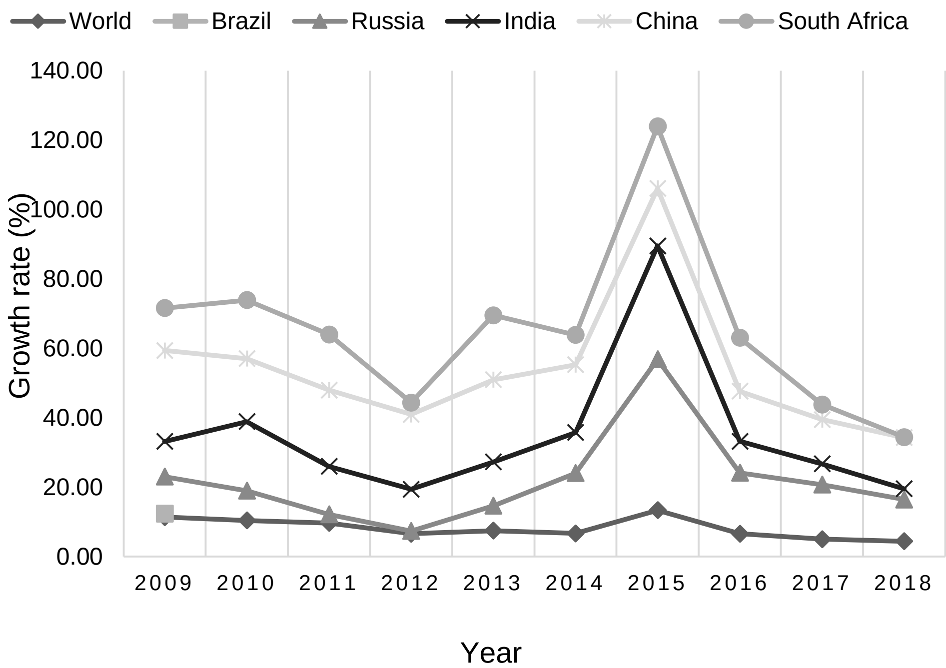


Figure 17: Bioeconomy publications trends in South Africa in comparison to world total and Brazil, Russia, India and China (BRICS), 2009-2018

As can be seen on Table 11, the number of bioeconomy publications for selected countries during 2008 to 2018 have shown a rising trend for this period, however, as was seen with South Africa, the growth rates are varied. Figure 17 shows that the BRICS countries experienced the lowest publications growth rate in 2012. The publications growth rate for the BRICS countries start to increase in 2013 and reached the highest growth rate in 2015. This increase is reflected in word total publications in terms of growth rate. In 2014, the WoS begin hosting the SciELO Citation Index covering Brazil, Spain, Portugal, the Caribbean, South Africa and 12 more Latin American countries. Further, in 2015, the Russian Science Citation Index was introduced to the WoS database to increase the citation of Russian publications by the world scientific community. The WoS was further expanded in 2015 to include the journals of the Emerging Sources Citation Index (ESCI) that includes peer-reviewed publications of regional importance and in emerging scientific field. These could explain the sudden increase and high growth rate of publications in 2015. Growth rates seem to be on a decline post 2015. South Africa had a growth rate of 12.2% in 2009 in terms of bioeconomy total publications and increased to 15.45% in 2016, however, the growth rate has declined to 4.31% and 0.16% in 2017 and 2018 respectively.

Table 12: Bioeconomy citations by year for world and Brazil, Russia, India, China and South Africa (BRICS), 2008-2015

Year	World	Growth rate (%)	Brazil	Growth rate (%)	Russia	Growth rate (%)	India	Growth rate (%)	China	Growth rate (%)	South Africa	Growth rate (%)
2008	4346195	1.00	101882		31415		122359		379953		27163	
2009	4389507	3.17	109458	7.44	30411	-3.20	137142	12.08	456329	20.10	26370	-2.92
2010	4528846	-3.42	109329	-0.12	32212	5.92	147864	7.82	535056	17.25	34275	29.98
2011	4373976	-5.83	111131	1.65	31837	-1.16	150502	1.78	586101	9.54	36831	7.46
2012	4118845	-6.35	108134	-2.70	39770	24.92	149003	-1.00	688981	17.55	26919	-26.91
2013	3857240	-10.49	109100	0.89	31809	-20.02	149611	0.41	676367	-1.83	33271	23.60
2014	3452774	-5.74	104375	-4.33	34720	9.15	145805	-2.54	689447	1.93	30068	-9.63
2015	3254618		95474	-8.53	27586	-20.55	136478	-6.40	642024	-6.88	28997	-3.56

The total citations for the BRICS countries are shown in Table 12. South Africa recorded 27,163 total citations in 2008 and 28,997 in 2015; a 6.8% increase. The total citations for all BRICS members gradually increased in general, although the growth rates were inconsistent. China experienced the highest growth increase at 69% growth rate during this period. Brazil recorded a decrease -6.29% in this period.

South Africa (Fig. 18) recorded the highest total citations in the year 2010 and the lowest total citations in 2012 among the BRICS countries.

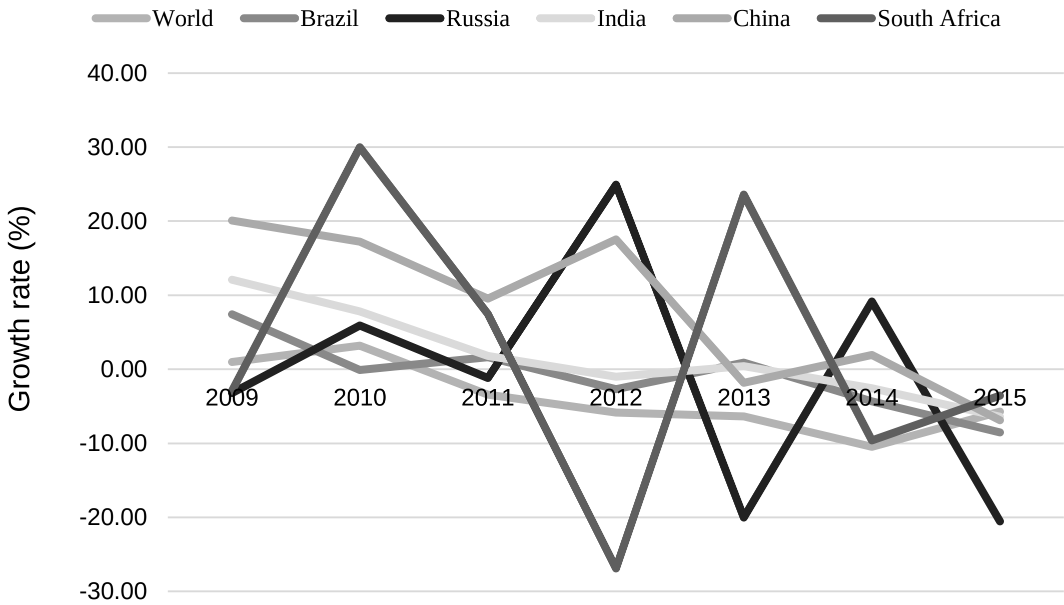


Figure 18: Bioeconomy citations trends in South Africa in comparison to Brazil, Russia, India, China and world, 2009-2015

In South Africa, most of the articles on bioeconomy appeared in the Journal PLoS One (468) followed by the South African Journal of Botany (335) (Table 13). The African Journal of Marine Science, Journal Water SA and Journal African Entomology followed with 155, 150 and 139 publications respectively for the period 2008 to 2018. The Journal PLoS One covers primary research from disciplines within science and medicine (Dash Nelson and Rae, 2016; Boë et al., 2017; Fuss et al., 2017; Gravett et al., 2017; Hallmann et al., 2017; Lance et al., 2017; Mack and Wrase, 2017). Scientific disciplinary performance of South Africa between 1996 and 2016 was the highest in the life sciences in terms of the number of publications, with a percentage share of 45.5 (NACI, 2018). This could explain the highest number of bioeconomy articles in the Journal PLoS One for South Africa.

Table 13: The top 20 journals publishing most articles on bioeconomy in South Africa, 2008-2018

Journal	Impact Factor*	No. of publications	Percentage of total	Country
PLoS One	2.776	468	2.46	United States of America
South African Journal of Botany	1.504	335	1.76	South Africa
African Journal of Marine Science	0.991	155	0.81	South Africa
Water SA	0.896	150	0.79	South Africa
African Entomology	0.536	139	0.73	South Africa
South African Journal of Science	1.351	121	0.64	South Africa
African Journal of Aquatic Science	0.75	118	0.62	South Africa
Scientific Reports	4.011	116	0.61	England
Biological Conservation	4.451	112	0.59	England
Biological Invasions	2.897	108	0.57	Netherlands
African Journal of Biotechnology	0.573	90	0.47	Kenya
Zootaxa	0.99	89	0.47	New Zealand
African Zoology	0.962	86	0.45	South Africa
SAMJ South African Medical Journal	1.316	85	0.45	South Africa
Molecular Phylogenetics and Evolution	3.992	83	0.44	United States of America
Journal of Ethnopharmacology	3.414	82	0.43	Ireland
Marine Ecology Progress Series	2.359	68	0.36	Germany
Molecules	3.06	68	0.36	Switzerland
Bioresource Technology	6.669	67	0.35	Netherlands
Diversity and Distributions	4.092	67	0.35	England

*Journal impact factor as published in the Journal Citation Reports of Clarivate Analytics for the year 2018.

Table 14 shows that environment, chemistry and plant sciences research attract substantially more attention than the biotechnology related disciplines. These findings confirm previous findings (Pouris, 2003; Pouris and Pouris, 2009b) that "active South African disciplines are those involving natural wealth, that is ecology, environment, geosciences, plant and animal sciences and space science". This observation is similar in the European Union where bioeconomy strategies focus on sustainability and environmental management such as reducing waste-streams of bio-resources and developing new products and economic value chains based on existing waste-streams (Bugge et al., 2016).

Table 14: Bioeconomy classification according to research domains in South Africa and their occurrence, for selected top 20, 2008-2018

Research area	Record count	Percentage of total
Environmental Sciences Ecology	3391	17.8
Chemistry	1419	7.45
Plant Sciences	1418	7.45
Science Technology Other Topics	1339	7.03
Biochemistry Molecular Biology	1125	5.91
Biotechnology Applied Microbiology	1071	5.63
Marine Freshwater Biology	937	4.92
Agriculture	920	4.83
Biodiversity Conservation	903	4.74
Engineering	884	4.64
Pharmacology Pharmacy	875	4.60
Zoology	766	4.02
Entomology	638	3.35
Geology	628	3.30
Microbiology	578	3.04
Water Resources	498	2.62
Evolutionary Biology	487	2.56
Materials Science	475	2.49
Infectious Diseases	437	2.30
Life Sciences Biomedicine Other Topics	403	2.12

As can be seen in Figure 19, South Africa collaborates the most with the United States of America, followed by England and Germany. These findings confirm previous findings (Pouris and Pouris, 2009b). Collaboration in bioeconomy in South Africa is substantially on par with the national average in terms of the top five collaborative countries (Figure. 20). It is noteworthy that previously the collaboration in biotechnology related disciplines was higher than the national average (Pouris and Pouris, 2009b).

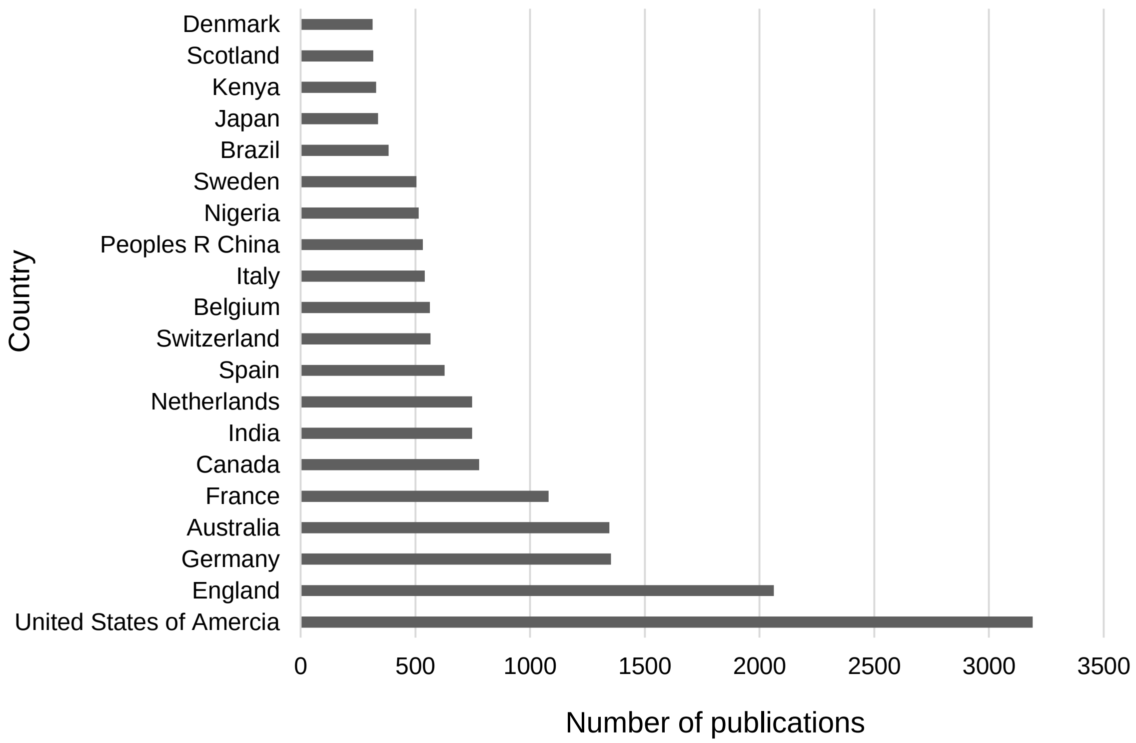


Figure 19: Bioeconomy collaboration profile of South Africa with other countries, 2008-2018

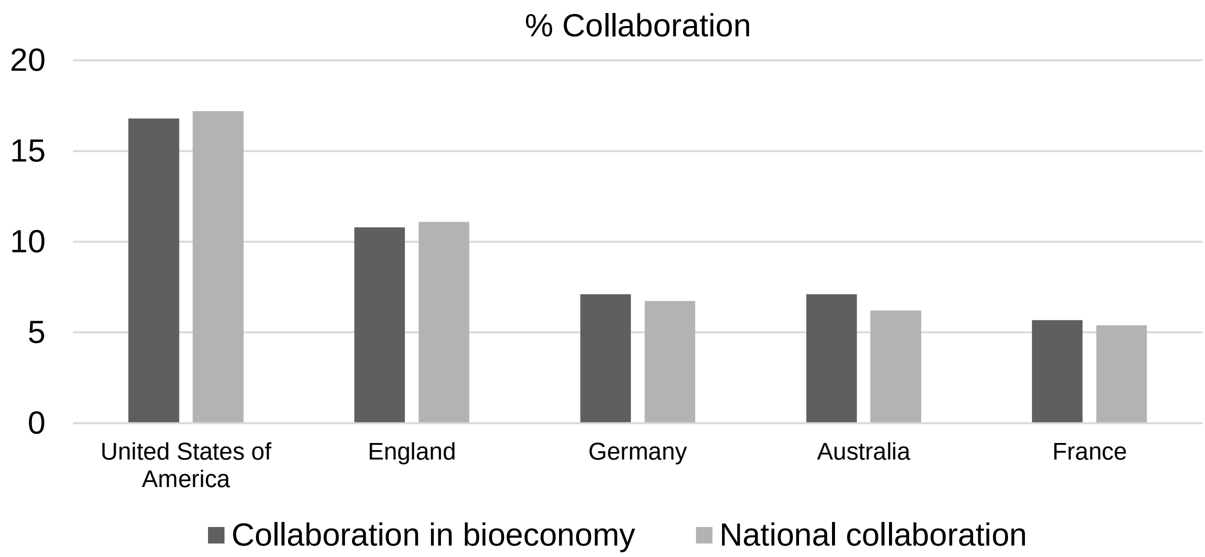


Figure 20: Bioeconomy collaboration network in South Africa

The publication outputs of various institutions are shown in Table 15. As expected, the University of Cape Town, University of Stellenbosch, University of KwaZulu-

Natal, University of Pretoria and University of Witwatersrand are leading with 13 408 South African bioeconomy publications. This conforms to the findings by Matthews (2012) and Makhoba and Pouris (2016). The findings represent 70.4% of all bioeconomy publications with at least one South African author for the period of 2008-2018. This observation is similar to NACIs observation on South African general publications where these top five universities account for 78.2% of the publications from universities (NACI, 2018).

Table 15: Top 20 producers of bioeconomy publications in South Africa, 2008-2018

Affiliation	Articles	% articles published
University of Cape Town	3238	17.01
University of Stellenbosch	3149	16.54
University of KwaZulu-Natal	2697	14.16
University of Pretoria	2415	12.68
University of Witwatersrand	1909	10.03
Rhodes University	1065	5.59
University of Johannesburg	1058	5.56
North West University	977	5.13
Council for Scientific and Industrial Research	776	4.08
University of the Free State	664	3.49
University of the Western Cape	592	3.11
Nelson Mandela Metropolitan University	628	3.30
University of the Free State	462	2.43
Tshwane University of Technology	425	2.23
University of Fort Hare	350	1.84
Tshwane University of Technology	425	2.23
University of Fort Hare	350	1.84
Durban University of Technology	270	1.42
Cape Peninsula University of Technology	257	1.35
University of Limpopo	248	1.30

5.5 PATENTOMETRIC ANALYSIS OF BIOECONOMY IN SOUTH AFRICA

Table 16: The number of biotechnology patents for BRICS, Egypt and Nigeria inventors granted at the EPO from 2008 to 2015, by priority date

Time	2008	2009	2010	2011	2012	2013	2014	2015
Country								
Brazil	13.6	7.3	6.1	2.9	7.8	7.3	5.3	0.8
Russia	11.1	16.7	12.9	22.8	17.3	9.8	8.2	3.3
India	34.2	27.5	23.1	23.9	23.2	23.5	19.6	29.2
China (People's Republic of)	51.2	68.1	73.4	84	60.4	81.8	66.5	40.8
South Africa	7.0	3.5	4.0	3.4	3.8	4.5	5.3	1.0
Egypt	0.5	0.0	0.0	1.0	0.3	0.0	0.0	0.0
Nigeria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
World	3965	3963	4006	4034	3764	3373	2217	911

Table 17: The number of pharmaceuticals patents for BRICS, Egypt and Nigeria inventors granted at the EPO from 2008 to 2015, by priority date

Time	2008	2009	2010	2011	2012	2013	2014	2015
Country								
Brazil	9.5	13.8	8.2	6.7	13.3	3.6	2.0	..
Russia	15.0	23.6	23.1	31.3	23.5	7.9	11.8	..
India	83.5	79.7	73.3	83.2	76.2	80.1	49.3	21.3
China (People's Republic of)	100.1	99.0	153.8	166.6	149.9	149.8	112.0	75.2
South Africa	4.5	4.1	4.0	2.6	4.0	2.0	3.7	2.0
Egypt	0.7	0.2	0.0	0.0	0.5	0.0	0.3	0.5
Nigeria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
World	4338	4200	4119	4060	3845	3294	2151	945

An analysis of biotechnology, pharmaceuticals and medical technology patents from the OECD patents by technology database identified between 1 to 7, 2 to 4.5 and 0.3 to 8.7 patents granted at the EPO (Table 16-18) respectively, with at least one South African inventor, by priority date between years 2008 and 2015. There were no patents recorded at the EPO for environment-related technologies for all the countries under investigation.

Table 18: The number of medical technology patents for BRICS, Egypt and Nigeria inventors granted at the EPO from 2008 to 2015, by priority date

Time	2008	2009	2010	2011	2012	2013	2014	2015
Country								
Brazil	12.7	7.0	7.8	5.3	1.0	8.4	11.0	6.9
Russia	16.1	5.9	7.4	14.7	12.2	6.0	3.6	5.5
India	17.6	22.2	36.9	17.7	12.5	17.2	23.1	18.7
China (People's Republic of)	27.3	35.5	43.3	62.4	72.0	90.2	89.5	56.4
South Africa	5.2	2.0	0.3	8.7	7.5	2.8	2.1	4.8
Egypt	1.0	1.2	0.5	0.0	1.2	1.2	0.0	-
Nigeria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
World	6395	6404	6458	6664	6348	6021	4488	2999

Analysis of biotechnology, pharmaceuticals and medical technology patents from the OECD patents by technology database identified between 1.3 to 10.1, 0.6 to 10.1 and 3.2 to 14.6 patents granted at the USPTO (Table 19-21) respectively, with at least one South African inventor, by priority date between years 2008 and 2016. There were 2 environment-related technologies patents recorded at the USPTO for South Africa in 2013 and 2015 and none for all the other countries investigated. The data is therefore not presented in the table format.

Table 19: The number of biotechnology patents for BRICS, Egypt and Nigeria inventors granted at the USPTO from 2008 to 2016, by priority date

Time	2008	2009	2010	2011	2012	2013	2014	2015	2016
Country									
Brazil	20	17.8	17.4	15	30.4	12.2	9.9	4.4	2
Russia	17.8	17.1	27.8	22.3	26.3	18.9	8.9	9	4.8
India	74.7	69.2	75.8	77.5	92	72.3	61	44.4	28.1
China (People's Republic of)	110.9	163.8	192.5	245.7	212	236.8	230.3	188.9	99.2
South Africa	8.6	6.8	6.3	7.4	4.8	7.5	10.1	1.3	-
Egypt	0.2	1.3	0.4	3.0	1.0	1.0	0.3	0.0	-
Nigeria	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.3	0.0
World	10307	10525	10833	10640	10101	9628	7432	4790	2798

Table 20: The number of pharmaceuticals patents for BRICS, Egypt and Nigeria inventors granted at the USPTO from 2008 to 2016, by priority date

Time	2008	2009	2010	2011	2012	2013	2014	2015	2016
Country									
Brazil	14.1	16.0	17.2	10.3	16.4	11.4	5.8	7.3	4.6
Russia	23.9	21.8	34.2	29.0	31.1	21.1	17.2	12.0	7.4
India	177.9	174.8	162.7	173.8	191.9	162.1	138.7	118.3	51.4
China (People's Republic of)	172.2	198.1	258.9	253.7	219.4	282.7	296.1	331.2	135.1
South Africa	8.3	6.3	6.6	7.9	5.5	7.5	10.1	1.0	0.6
Egypt	0.0	0.5	0.5	3.3	0.3	1.3	2.4	0.5	1.8
Nigeria	0.0	0.2	1.0	0.0	0.0	0.0	0.0	-	0.0
World	10062	9895	9411	9113	8799	8475	6933	4932	2355

Table 21: The number of medical technology patents for BRICS, Egypt and Nigeria inventors granted at the USPTO from 2008 to 2016, by priority date

Time	2008	2009	2010	2011	2012	2013	2014	2015	2016
Country									
Brazil	20.5	18.0	18.2	20.9	11.6	17.6	17.4	8.0	3.1
Russia	84.9	17.5	18.1	29.4	21.0	14.9	13.2	8.9	..
India	28.2	61.1	67.7	75.0	57.0	58.5	92.0	71.0	59.3
China (People's Republic of)	107.6	132.6	165.9	200.4	215.8	321.3	340.8	299.2	191.5
South Africa	14.6	6.7	7.5	11.9	10.0	5.9	6.5	3.2	6.4
Egypt	2.0	2.8	2.3	3.2	1.3	0.2	1.3	-	0.0
Nigeria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
World	16265	16666	17579	18343	18802	19620	16471	12487	8085

The number of South African biotechnology, pharmaceuticals and medical technology patents have shown decreasing trends during the period investigated. For example, South Africa in biotechnology record 7 patents in 2008 and 1 patent in 2015 at the EPO, and 8.6 to 1.3 at the USPTO during 2008 and 2015 respectively. These decreasing trends were observed in other members of the BRICS, Egypt, Nigeria and world total. The patents granted patterns at the EPO and the USPTO shows that the knowledge base in the bioeconomy for South Africa is the smallest compared to other BRICS countries.

Table 22: The top ten biotechnology patenting organisations for the Brazil, Russia, South Africa and Egypt at the EPO, 2008 to 2016

Brazil		Russia		South Africa		Egypt	
Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents
Fundacao Oswaldo Cruz	11	Ajinomoto Co Inc	46	Council for Scientific and Industrial Research	20	Veterinarmedizinische Universitat Wien	2
Braskem SA	10	Epshtein Oleg Iliich	16	Stellenbosch University	20	Shawky Sherif Mohamed	2
Fundacao Butantan	8	Obschestvo S Ogranichennoi Otvetstvennostiyu Pharmenterprises	10	University of Cape Town	17	Samir Tamer Mohamed	2
E I Du Pont De Nemours And Company	7	Nextgen Company Limited	8	University of Pretoria	15	Heart Biotech Limited	2
Erasmus University Medical Center Rotterdam	7	Tets Viktor Veniaminovich	6	University of Witwatersrand	10	Azzazy Hassan Mohamed Ei Said	2
Uniao Brasileira De Educacao E Assistencia Mantenedora Da Pucrs	7	Tets Georgy Viktorovich	6	Kapa Biosystems Inc	7	University of Southern California	1
Empresa Brasileira De Pesquisa Agropecuaria Embrapa	6	Zakrytoe Aktsionernoe Obschestvo Pharm Sintez	5	University of the Free State	7	The Governing Council Of The University Of Toronto	1
Universidade De Sao Paulo Usp	6	Aktsionernoe Obschestvo Pharm Sintez	5	Northwest University	6	Snead Malcolm L	1

Universidade Estadual Paulista Julio De Mesquita Filho Unesp	6	Zamerton Holdings Limited	4	Medicago Inc	4	Ramadan Mohamed	1
Universidade Federal Do Rio De Janeiro	6	The Broad Institute Inc	4	Mitsubishi Tanabe Pharma Corporation	4	Mounir Maha Mohamed Fouad Mounir	1

Table 23: The top ten pharmaceuticals patenting organisations for Brazil, Russia, South Africa and Egypt at the EPO, 2008 to 2016

Brazil		Russia		South African		Egypt	
Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents
Biolab Sanus Farmaceutica Ltda	19	Alla Chem Llc	33	University Of the Witwatersrand Johannesburg	29	Heart Biotech Pharma Limited	5
Fundacao Oswaldo Cruz	13	Obshestvo S Ogranichennoj Otvetstvennostju Parafarm	31	University Of Cape Town	18	Veterinarmedizinische Universitat Wien	2
Natura Cosmeticos Sa	12	Ivashchenko Andrey Alexandrovich	27	Council for Scientific and Industrial Research	13	University Of Pretoria	2
Fundacao Butantan	11	Tets Viktor Veniaminovich	24	Stellenbosch University	11	University Of KwaZulu-Natal	2
Universidade Federal De Minas Gerais Ufmg	8	Tets Georgy Viktorovich	20	University Of Pretoria;8	8	Instytut Immunologii I Terapii Doswiadczalnej Pan	2
Universidade De Sao Paulo Usp	8	Ivachtchenko Alexandre Vasilievich	16	Mitsubishi Tanabe Pharma Corporation	6	Heart Biotech Limited	2
Universidade Federal Do Rio Grande Do Sul Ufrgs	7	Epshtein Oleg Iliich	16	Medicago Inc	6	HC Pharma Ag	2
Ems Sa	7	Obschestvo S Ogranichennoi Otvetstvennostiyu Pharmenterprises	14	Agricultural Research Council	5	University Of Southern California	1
Universidade Federal Do Rio De Janeiro	6	Savchuk Nikolay Filippovich	10	North West University	4	Ucb Pharma Gmbh	1

Rhodia Poliamida E Especialidades Ltda	6	Joint Stock Company Biocad	10	Nektium Pharma Sl	4	The USA as Represented by the Secretary Department Of Health and Human Services	1

Table 24: The top ten medical technologies patenting organisations for Brazil, Russia, South Africa and Egypt at the EPO, 2008 to 2016

Brazil		Russia		South African		Egypt	
Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents
Johnson Johnson Consumer Inc	27	Align Technology Inc	18	University Of Cape Town	18	Hafez Mahmoud Alm El Din	4
3m Innovative Properties Company	14	Samsung Electronics Co Ltd	13	Strait Access Technologies Holdings Pty Ltd	13	Endo Tools Therapeutics Sa	4
Jjgc Industria E Comercio De Materiais Dentarios Sa	11	Healbe Corporation	11	Southern Implants Pty Ltd	11	The American University In Cairo	2
Cook Medical Technologies Llc	10	Balakin Vladimir Yegorovich	10	Ethicon Endo Surgery Inc	8	Research Foundation For Medical Devices	2
Rhodia Poliamida E Especialidades Ltda	7	Covidien Lp	9	University Of The Witwatersrand Johannesburg	7	Kspine Inc	2
Johnson Johnson Industrial Ltda	7	Tyco Healthcare Group Lp	7	Stellenbosch University	5	K2m Inc	2
Mcneil Ppc Inc	6	Asml Netherlands Bv	7	Oosthuizen Christiaan Rudolf	5	Helmholtz Zentrum Geesthacht Zentrum Fur Material Und Kustenforschung Gmbh	2
Johnson Johnson Do Brasil Industria E Comercio De	6	Origin Inc	6	Ethicon Llc	5	Heart Biotech Limited	2

Produtos Para Saude Ltda							
Epygon	6	Johnson Johnson Vision Care Inc	6	University Of The Free State	4	Salem Ahmed Abdel Moghny	1
Zammi Instrumental Ltda	5	Globetek 2000 Pty Ltd	6	The University Of Lincoln	4	Noordeen Mohamad Hamza Hilali Ideros	1

South Africa, for example, needs to increase its patents registrations in biotechnology at the EPO by a factor of 1.6, 3.1, 6.3 and 16 to produce an equivalent volume of knowledge production to Brazil, Russia, India and China respectively, and by a factor of 2.4, 2.9, 11 and 32 at the USPTO to produce an equivalent volume of knowledge production to Brazil, Russia, India and China respectively.

The patent outputs of various institutions at the EPO are shown in Table 23, 24 and 25. In South Africa, the Council for Scientific and Industrial Research (CSIR), University of the Witwatersrand and University of Cape Town are leading patenting organisaitons in biotechnology, pharmaceuticals and medical technologies respectively. It is noteworthy that these leading patenting organisations in South Africa at the EPO are academic institutions and a state-owned institution. In Brazil, Russia and Egypt the leading patenting organisations at the EPO are private entities or private individuals. There were no patents recorded from Nigeria at the EPO during this investigation and therefore data on patenting organisaitions from Nigeria at the EPO is not presented.

The patent outputs of various institutions at the USPTO are shown in Table 25, 26 and 27. The University of Stellenbosch, University of Cape Town and a private individual recorded the most patents for South Africa in biotechnology, pharmaceuticals and medical technologies respectively. Patents grants at the USPTO of the most prolific assignees in South Africa in all the technologies between 2011 and 2015 were mainly individual owned patents, with three universities (Witwatersrand, Cape Town and Stellenbosch) in the top 10 (NACI 2018). In Brazil, Russia and Egypt the leading patenting organisations at the USPTO are mainly private entities or private individuals. Nigeria did not produce considerable patents at the USPTO and therefore patenting organisaitions from Nigeria were not included in the analysis.

Table 25: The top ten biotechnology patenting organisations for the Brazil, Russia, South Africa and Egypt at the USPTO, 2008 to 2015

Brazil		Russia		South Africa		Egypt	
Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents
Pioneer Hi Bred International Inc	16	Oleg Iliich Epshtein	8	Stellenbosch University	8	Purdue Research Foundation	6
Fundação Oswaldo Cruz (Fiocruz)	9	Max-Planck-Gesellschaft zur Föerderung der Wissenschaften e.V.	4	University of the Free State	6	Texas A&M University System	2
Fundação Butantan	8	Alloferon Inc	2	University of Cape Town	4	University of Arkansas	2
Oxford University Innovation Ltd	5	Daphot Enterprises Limited	2	University of Pretoria	3	American University in Cairo	1
Universidade Estadual Paulista "Julio de Mesquita Filho"	5	HyTest Ltd	2	BHP Billiton SA Ltd	2	Instytut Immunologii i Terapii Doswiadczalnej PAN	1
Alvos - Consultoria, Desenvolvimento e Comercializacao de Produtos Biotecnologicos S/A	3	Nextgen Company Limited	2	North West University	2	Moustafa Ahmed El-Shafie	1
BASF SE	2	Nicolai Vladimirovich Bovin, Stephen Micheal Henry and Stephen Robert Parker	2	Sasol Technology Pty Ltd	2	Pioneer Hi Bred International Inc	1
Erasmus University Medical Center	2	Obschestvo S Ogranichennoi Otvetstvennostiyu Pharmenterprises	2	Council for Scientific and Industrial Research	1	University of Guelph	1
Indiana University Research and Technology Corporation	2	Pharmenterprises Biotech LLC	2	ERA Biotech S.A.	1	University of South Carolina	1

Proteimax Biotecnologia Ltda	2	Pioneer Hi Bred International Inc	2	Lallemand Hungary Liquidity Management LLC	1	University of Toronto	1

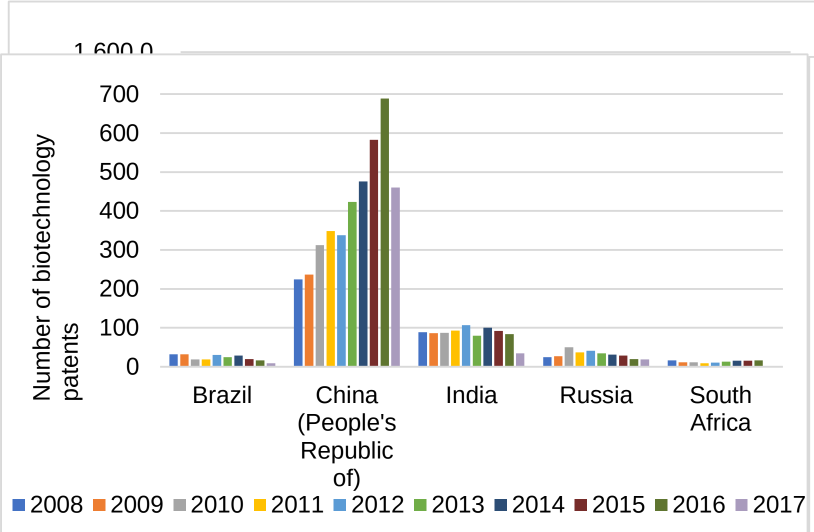
Table 26: The top ten pharmaceuticals patenting organisations for the Brazil, Russia, South Africa and Egypt at the USPTO, 2008 to 2015

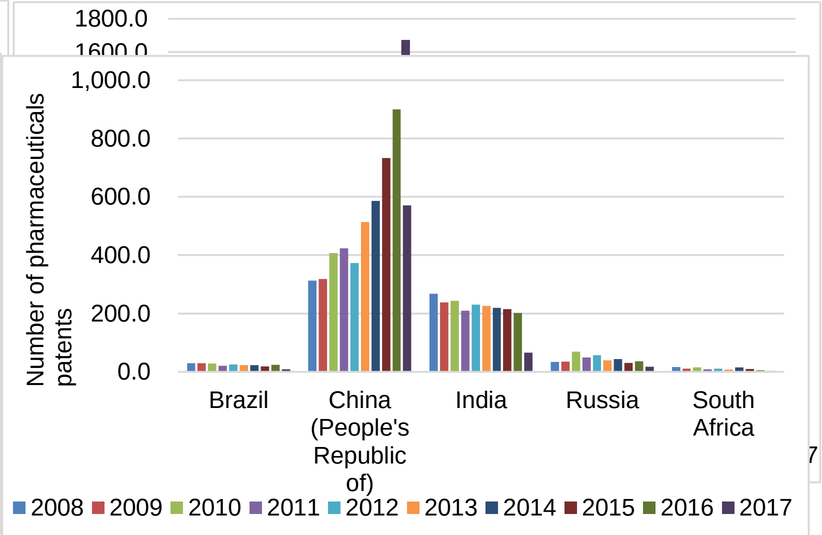
Brazil		Russia		South African		Egypt	
Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents
Fundacao Oswaldo Cruz	17	Oleg I. Epshtein	11	University of Cape Town	5	King Saud University	5
Fundacao Butantan	8	A V Topchiev Institute of Petrochemical Synthesis	5	University of the Witwatersrand	5	University of Kansas	3
US Department of Health and Human Services	6	Corium International Inc	5	North West University	3	Texas A&M University System	2
Natura Cosmeticos SA	5	NextGen Co Ltd	5	Stellenbosch University	3	University of Arkansas	2
Empresa Brasileira de Pesquisa Agropecuaria	4	Mitotech SA	4	Environ Skin Care Pty Ltd	2	Heart Biotech Pharma Ltd	1
Doris Hexsel	3	Parapharm LLC	4	South African Nuclear Energy Corp Ltd	2	Pharco Pharmaceuticals	1
Universidade Federal de Minas Gerais	3	US Department of Health and Human Services	3	Shimoda Biotech Pty Ltd	2	STC UNM	1
Alexandre Eduardo Nowill	2	Pharmenterprises OOO	3	University of Johannesburg	2	University of Guelph	1
Biotick Pesquisa E Desenvolvimento Tecnologico Ltda,	2	Alloferon Inc	2	University of Pretoria	2	University of KwaZulu-Natal	1

Commonwealth Scientific and Industrial Research Organization	2	Alternative Innovative Technologies LLC	2	Warburton Technology Ltd	2	University of Pretoria	1

Table 27: The top ten medical technologies patenting organisations for the Brazil, Russia, South Africa and Egypt at the USPTO, 2008 to 2015

Brazil		Russia		South African		Egypt	
Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents	Patenting organisation	Number of patents
Colgate Palmolive Co	2	Aktsionernoe Obschestvo Zakrytogo Tipa "Ostim"	2	Fourie Phillippus J	2	Population Council Inc	3
Gama Jose M	2	Ethicon Inc	2	Grieshaber and Co AG Schaffhausen	2	El Hadary Khaled A H	1
Intermed Equipamento Medico Hospitalar Ltda	2	Life Support Technologies Inc	2	Latex Products Ltd Pty	2	Mohamed Kaled Mohamed El Hatu	1
Johnson and Johnson Consumer Companies LLC	2	Shturman Cardiology Systems Inc	2	Preller Siegfried F	2	Medtronic AVE Inc	1
Antoine Jean Henri Robert	1	Abramov; Vladimir V., Novikov; Juriy V.	1	South African Inventions Development Corp	2	University of South Florida	1
Beiersdorf AG	1	Advanced Renal Technologies Inc	1	Surgi International Ltd Pty	2	Hafez Mahmoud Alm El Din	1
Dario Fauza	1	Archimedes Technology Group Inc	1	Warburton Technology Ltd	2	K2M Inc	1
De Resende; Jefferson G.	1	Bashikirov; Alexei B.	1	Westdyk Alan M	2	Research Foundation For Medical Devices	1
Edwards Lifesciences Corp	1	Elena Valerievna Tkatchouk	1	Widgerow; Alan D, Chait; Laurence A	2	The American University In Cairo	1
ELC Produtos de Seguranca Industria e Comercio Ltda	1	Felton International Inc	1	Arrow International LLC	1	Noordeen Mohamad Hamza Hilali Ideros	1





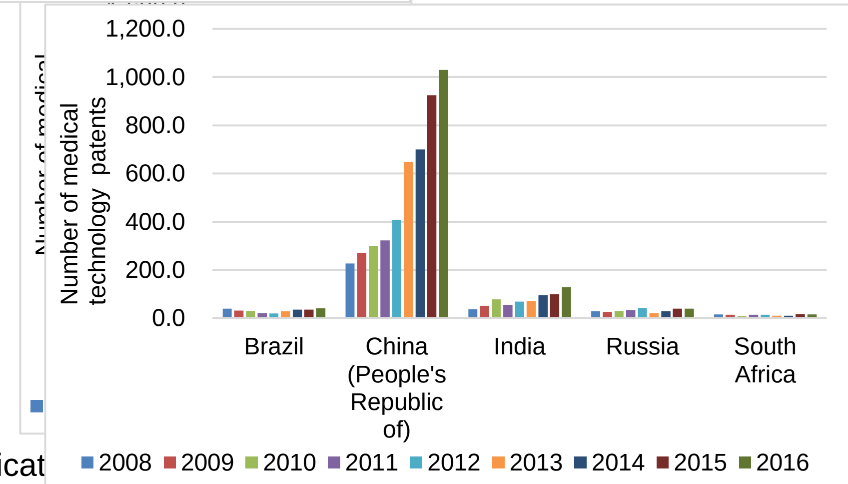


Figure 21: The patent applicat 008 to 2017, by inventor

Figure 22: The IP5 patent families for the BRICS cumulative from 2008 to 2017, by inventor and priority date

The biotechnology, pharmaceuticals and medical technology patent applications (Fig. 21) for BRICS Countries filed under the PCT shows South Africa recorded the least number of patents while China recorded the most number of patents during this period. China showed consistent growth in the number of patent applications filed under the PCT during this period compared to other members of the BRICS countries, which showed a decline in the number of patents during the period under investigation. The OECD (2008, 2009e) findings showed that the number of biotechnology patent applications for all countries filed under the PCT decreased by an average rate of 3.6% yearly between 2000 and 2006. South Africa needs to increase its medical technology patents applications filed at the PCT by a factor of 31 to produce an equivalent volume of knowledge production to China.

Figure 22 shows the number biotechnology, pharmaceuticals and medical technology patents for BRICS nations that belongs to the IP5 patent family. As expected, South Africa recorded the least number of patents while China recorded the most number of patents in this category. South Africa needs to increase its number of patents in the five offices by a factor of 33 and 1.9 to produce an equivalent volume of knowledge production in biotechnology to China and Brazil respectively. The OECD (2018b) provided patent statistics on biotechnology and nanotechnology based on the IP5 patent families from 1990 to 2012 and observed that, since 2008 biotechnology patents seem to be on a decline. This observation is similar in the study for IP5 patent families for South Africa, Russia, India and Brazil. China shows an increasing trend in terms of IP5 patent families during the period under investigation.

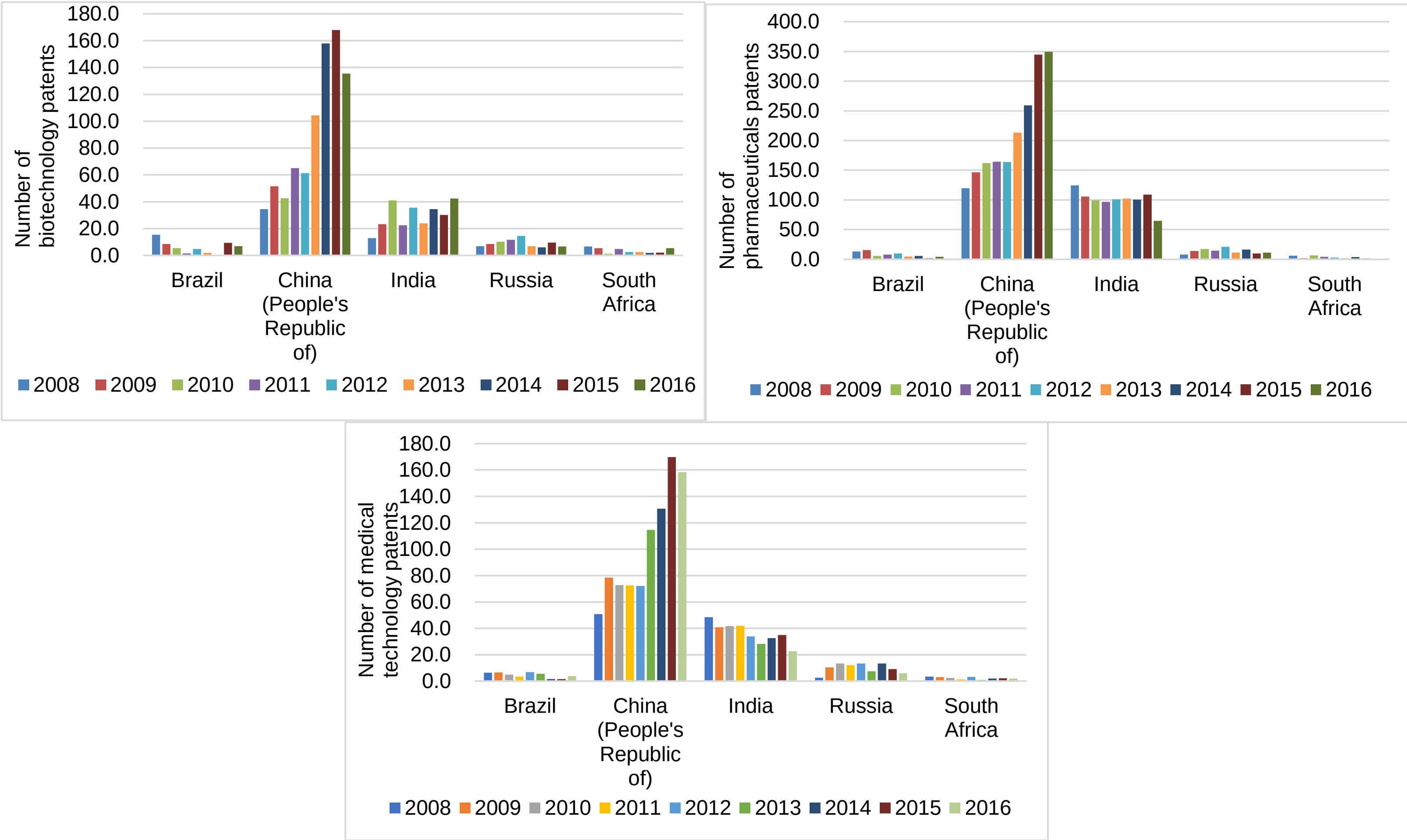


Figure 23: The triadic patent families for the BRICS cumulative from 2008 to 2016, by inventor and priority date

Figure 23 shows the number of biotechnology, pharmaceuticals and medical technology patents for BRICS nations that belong to the triadic patent family. China recorded the highest number of patents that belong to the triadic patent family, followed by India. South Africa recorded the lowest number of patents that belong to the triadic patent family during the selected period. Brazil, India, Russia and South Africa showed a decreasing trend in terms of the number of patents that belong to triadic patent families. The OECD statistics (OECD, 2008) reported that since around 2001 the rate of growth of the total number of triadic patent families has been on a decline. China, however, observed a positive growth rate during the same period.

It is recorded in the literature that patents with a large number of patent families are valuable (Harhoff et al., 2002; Wang, 2007). Patents filed at the PCT and those that belong to IP5 and triadic families can therefore be classified as important patents having been filed in multiple authorities (OECD, 2020).

Table 28: The total patents registered at the CIPC from 2008 to 2018

Year	Total patents	Total patents by South Africans	Total patents by non-South Africans
2008	7713	936	6777
2009	7290	840	6450
2010	6958	871	6087
2011	5437	623	4814
2012	6314	733	5581
2013	4875	520	4355
2014	5131	465	4666
2015	4557	436	4121
2016	4607	446	4161
2017	5504	609	4895
2018	7262	711	6551

The total patents (Table 28) registered at the CIPC during the period under investigation indicates a generally decreasing trend (Fig. 24) for both patents registered by South African and non-South African residents until 2015, and the growth rates begin to increase sharply post-2015.

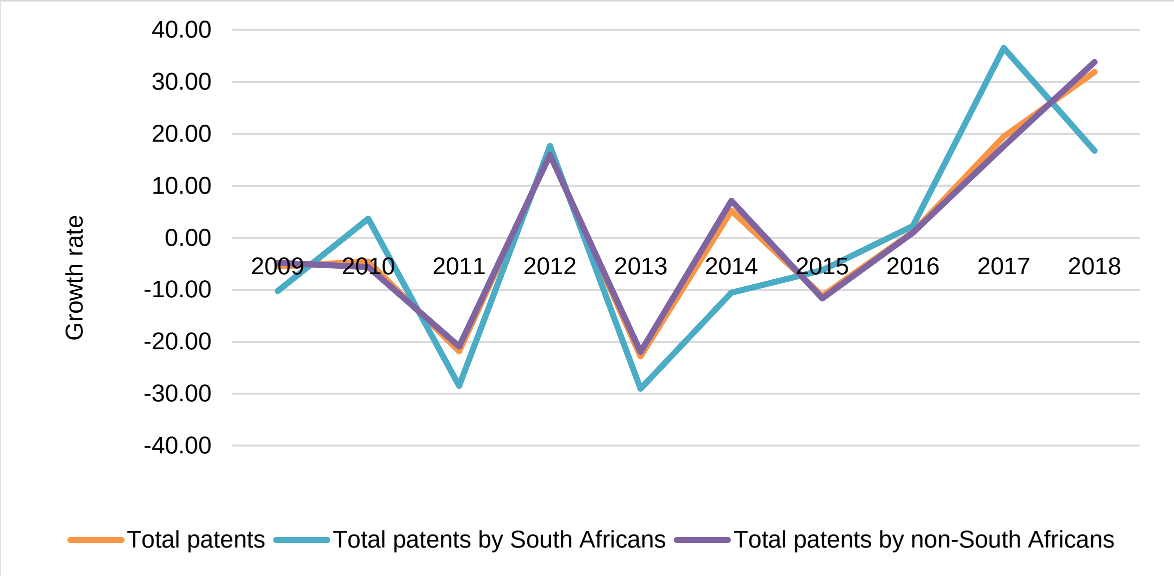


Figure 24: The patents growth rate at the CIPC from 2008 to 2018

Table 29: The total biotechnology patents registered at the CIPC from 2008 to 2018

Year	Total biotechnology patents	Total biotechnology patents registered by South Africans	Total biotechnology patents registered by non-South Africans
2008	2297	57	2240
2009	2318	76	2242
2010	2114	58	2056
2011	1617	49	1568
2012	1833	54	1779
2013	1349	49	1300
2014	1436	26	1410
2015	1165	42	1123
2016	1189	19	1170
2017	1362	27	1335
2018	1845	41	1804

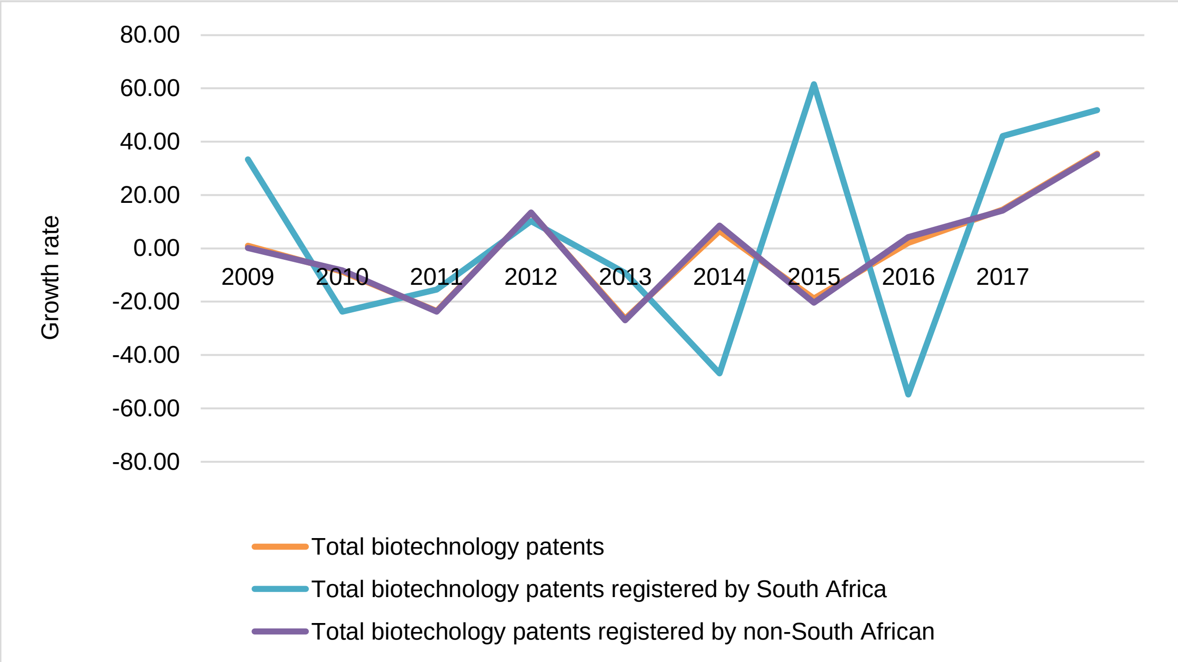
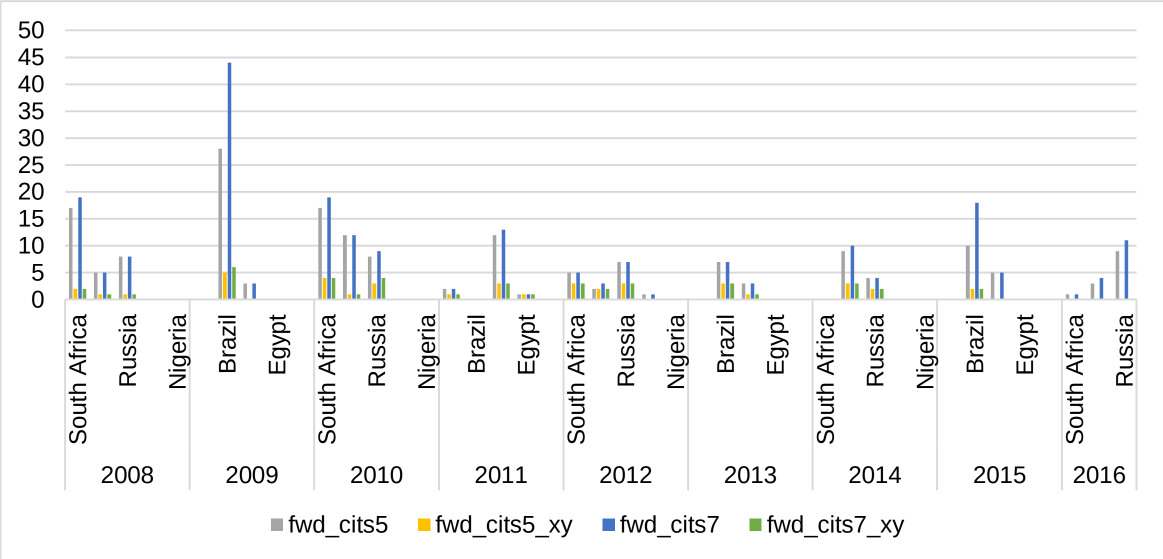


Figure 25: The biotechnology patents growth rate at the CIPC from 2008 to 2017

In terms of biotechnology patents (Fig. 25), the growth rate of the total biotechnology patents registered by South Africans was unparalleled by the growth rates for the total biotechnology patents and the total biotechnology patents registered by non-South Africans. Since 2008, the total biotechnology patents and the total biotechnology patents registered by non-South Africans at CIPC have been at a decline (Table 29). For total biotechnology patents registered by South Africans, results vary. The total biotechnology patents registered by South Africans at the CIPC are less, compared to total biotechnology patents registered by non-South Africans. According to reports (NACI, 2017:33) since 2011 at WIPO Statistics Data Center, up to two thirds of the patents granted for South Africa were to non-residents as compared to international situation where the majority of patents are granted to local residents. Moreover, as the CIPC move towards becoming the patents examination authority, the number of patents by South Africans could decline even further as non-qualifying patents may be eliminated and the cost of registration is expected to increase. It is said South Africa's patents registrations is amongst the cheapest in the world. According to Pouris and Pouris (2011), the non-examining patent system is detrimental to innovation and economic development as it makes the system prone to granting patents on known or only trivially modified inventions that confer potential market power.

Figure 26: Biotechnology forward citations trends registered in the EPO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2016



In terms of the biotechnology, pharmaceuticals and medical technologies forward citations (Fig. 26, 27 and 28) trends registered in the EPO, South Africa recorded higher number of forward citations than Brazil for biotechnology during the years 2008 and 2010. This is consistent with data on the world forward citations and forward citations received as x, i or y, average index by economy where South Africa was slightly above Brazil during the year 2009 (Squicciarini et al. 2013). For the other years in terms of forward citations at the EPO, South Africa was comparable to Brazil and Russia for biotechnology. South Africa seems to be lagging behind Brazil and Russia for pharmaceuticals and medical technologies in terms of forward citations recorded at the EPO. In comparison to Egypt and Nigeria, South Africa recorded the highest number of forward citations at the EPO for all the technologies investigated.

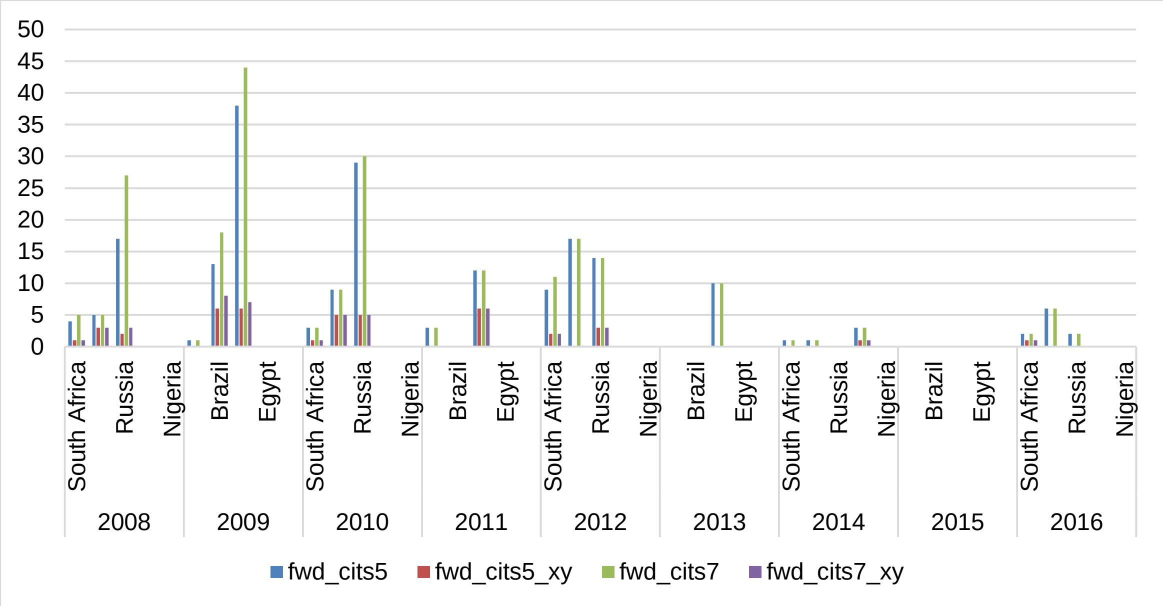


Figure 27: Pharmaceuticals forward citations trends registered in the EPO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2016

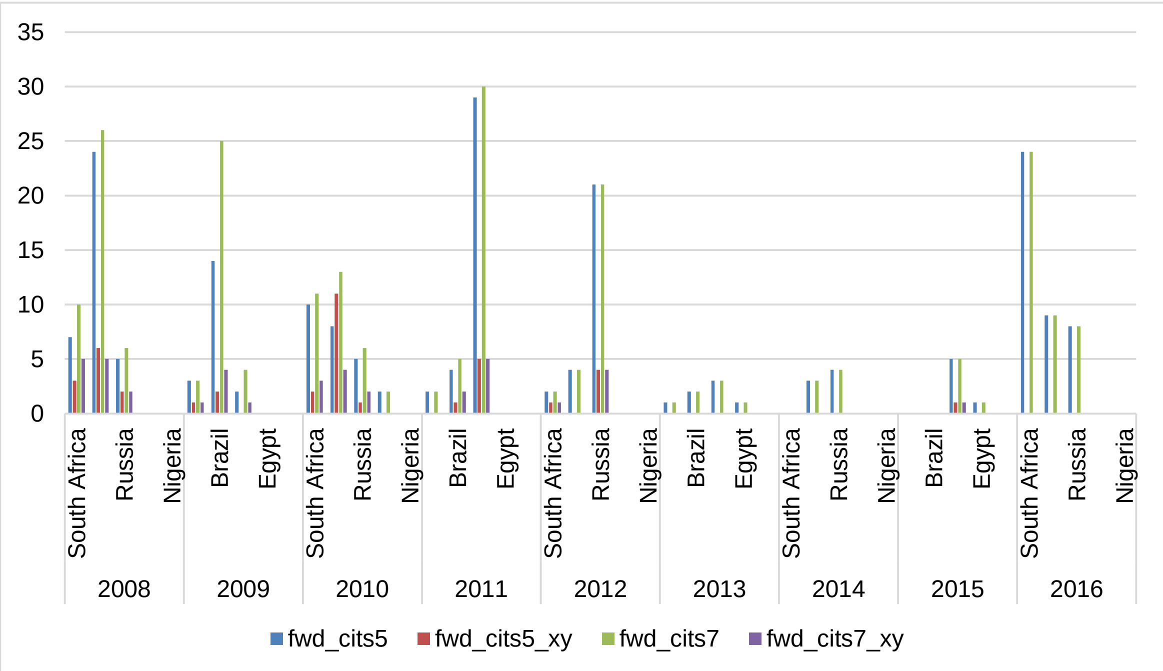


Figure 28: Medical technologies forward citations trends registered in the EPO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2016

The biotechnology, pharmaceuticals and medical technologies backward and non-patent literature citations trends registered at the EPO (Fig. 29, 30 and 31) shows South Africa recorded the lowest number of citations compared to that of Brazil and Russia but the citations were higher than that recorded for Egypt and Nigeria. This is consistent with the world citations to npl, index and average by economy where South Africa does not appear in the top 20 as compared to the other members of the BRICS group during 1999 and 2009 (Squicciarini et al. 2013).

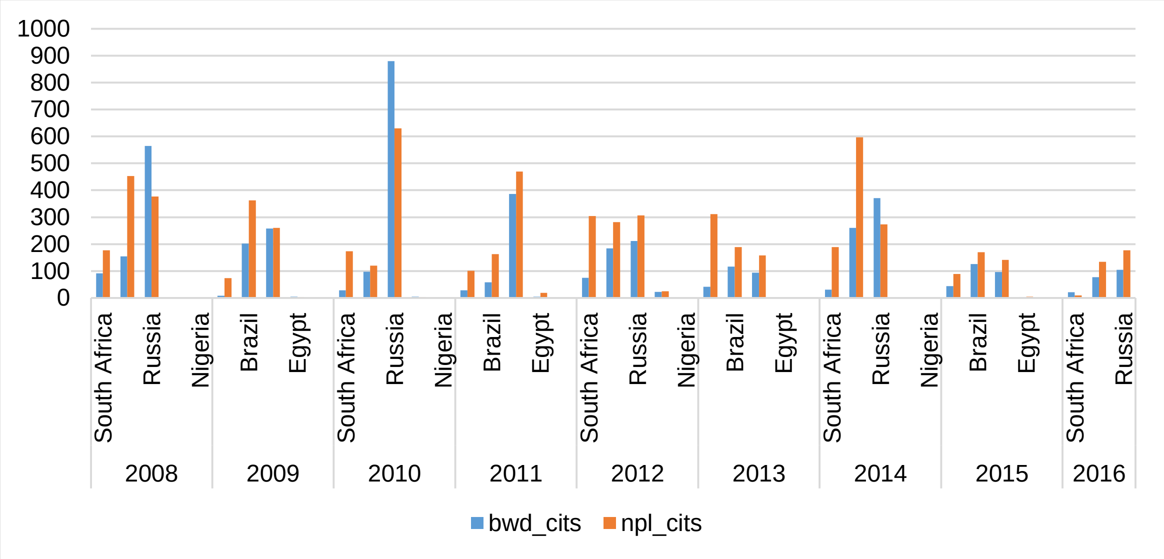


Figure 29: Biotechnology backward and non-patent literature citations trends registered in the EPO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2016

As the distribution of backward citation, non-patent literature and forward citations at the USPTO per country chart shows (Fig. 32, 33 and 34), the period considered appears to show similar citation patterns for South Africa, Brazil and Russia for biotechnology. South Africa recorded the lowest number of citations compared to Brazil and Russia, while Russia recorded the highest number of citations for biotechnology and pharmaceuticals patents. South Africa generally recorded higher number of citations compared to Brazil for medical technologies at the USPTO. South Africa recorded highest number of citations in all the technologies compared to Egypt and Nigeria

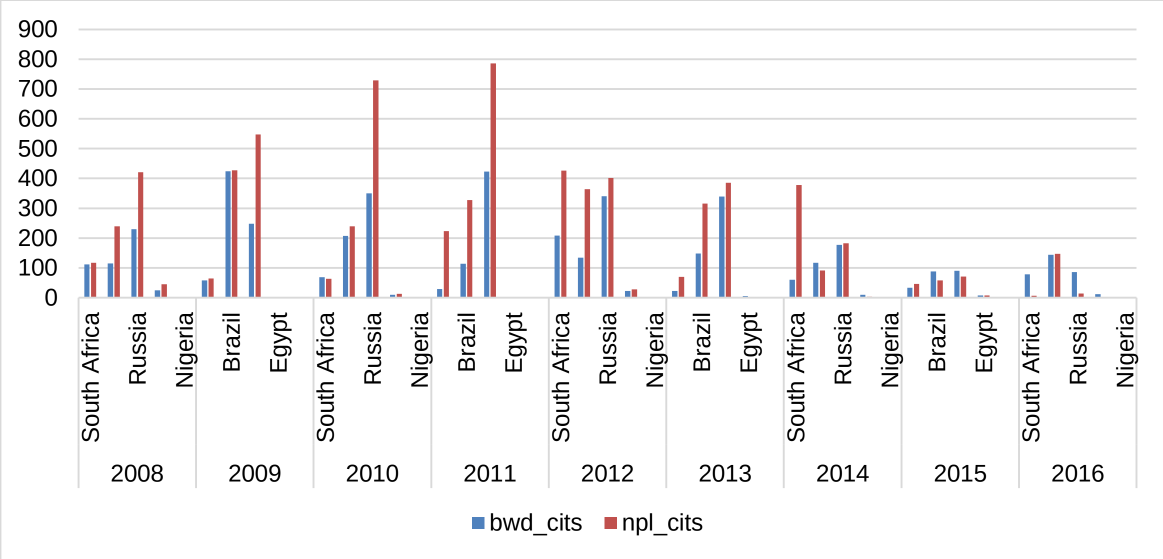


Figure 30: Pharmaceuticals backward and non-patent literature citations trends registered in the EPO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2016

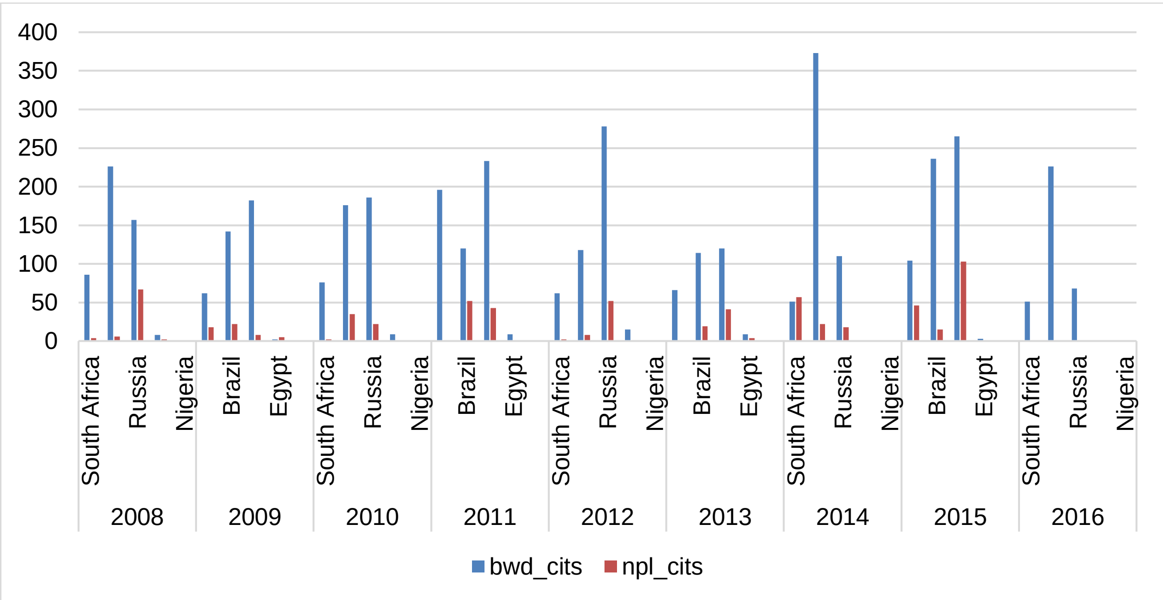


Figure 31: Medical technologies backward and non-patent literature citations trends registered in the EPO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2016

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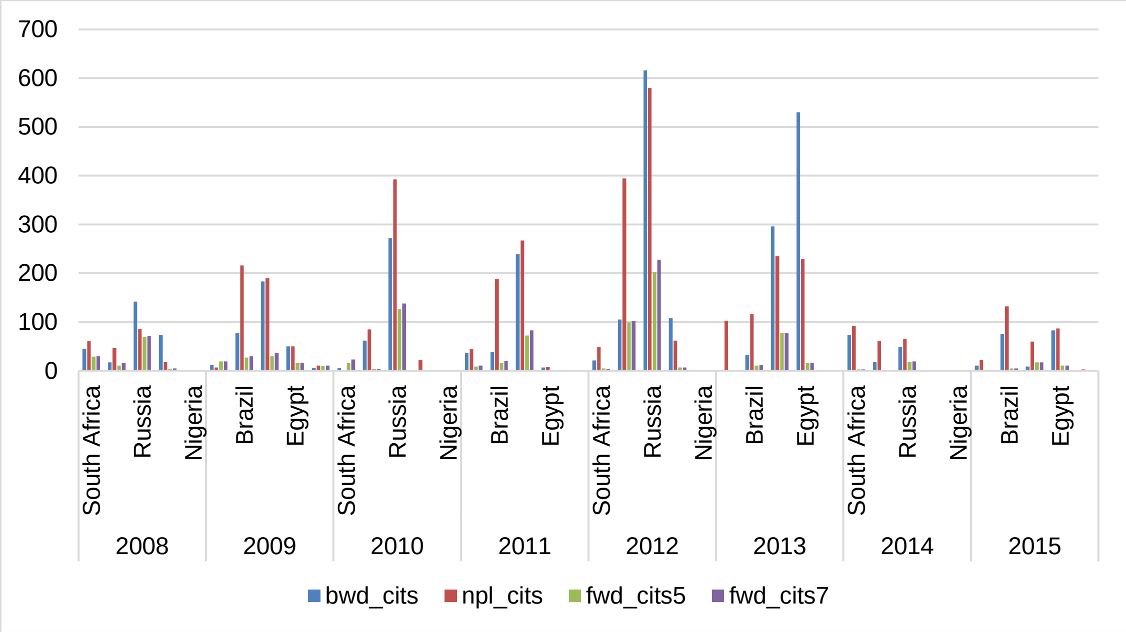

Figure 32: Biotechnology backward, non-patent literature and forward citations trends registered in the USPTO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2015

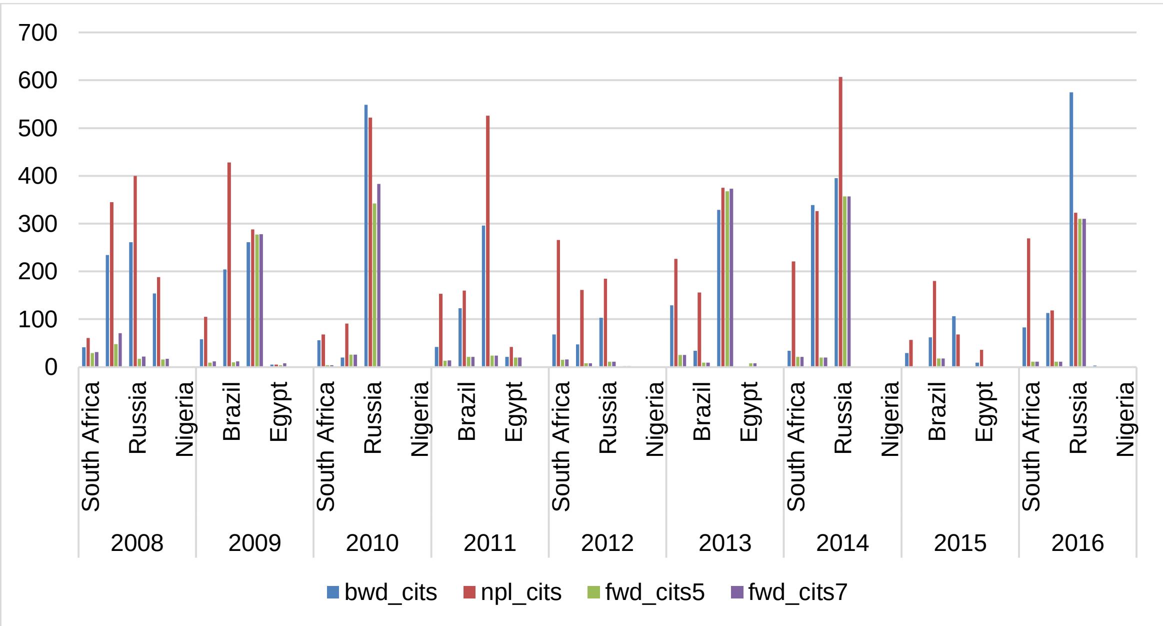

Figure 33: Pharmaceuticals backward, non-patent literature and forward citations trends registered in the USPTO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2015

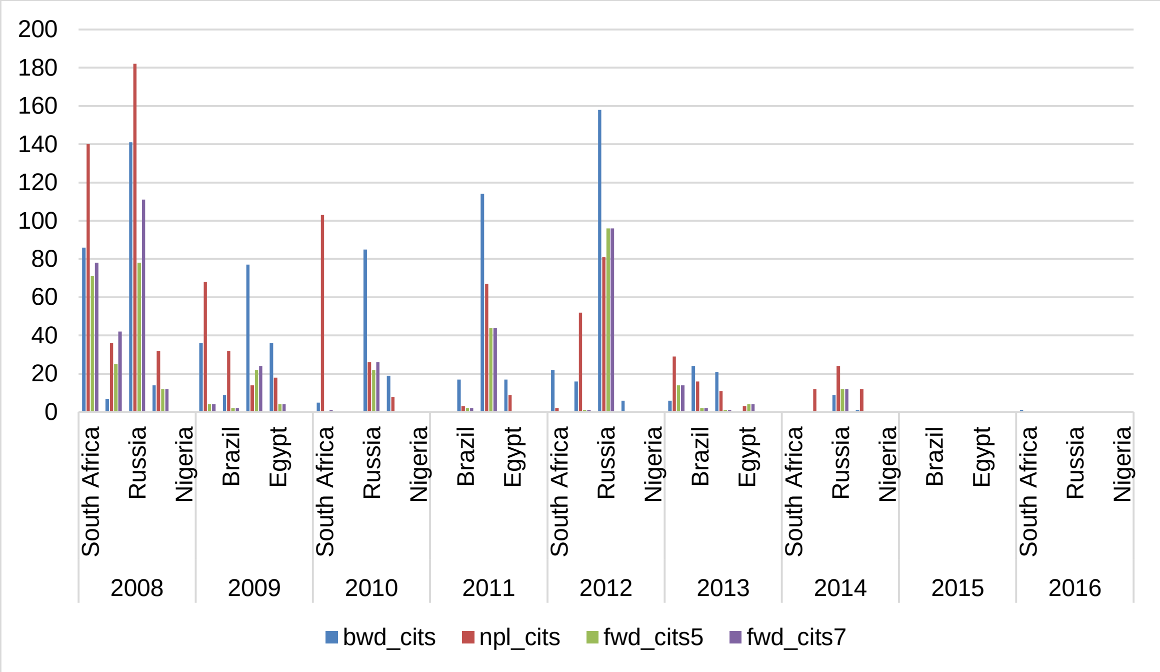

Figure 34: Medical technologies backward, non-patent literature and forward citations trends registered in the USPTO for South Africa in comparison to Brazil, Russia, Egypt and Nigeria, 2008-2015

5.6 ANALYSIS OF THE NUMBER OF FIRMS IN THE BIOECONOMY IN SOUTH AFRICA

The list of active bioecomomy frims in South Africa as of Janaury 2021 are presented in Table 30. The majority of the firms identified were in the health sector, in particular, medical devices and the pharmaceuticals companies.

Table 30: List of bioeconomy firms in South Africa

Industry sector	Agriculture	Health	Industry and environment	IKS	Research Councils	Not allocated	Total
Number	196	367	88	35	4	40	730

In Agriculture, companies were mainly seed companies, both non-GMOs and GMOs. Science councils and research institutions included the ARC, CSIR, SAMRC and MINTEK. Science councils sell their outputs at an economic price and were included in the count (OECD, 2002: 55). Patra and Muchie (2017) recorded 692 firms working in life sciences related areas in their database. Their database included universities and not for profit research organisations which were omitted from this study. As articulated in this thesis, universities and service organisations, including organisations involved in marketing and distribution, were excluded in the counting as they either do not meet the OCED definition of a biotechnology firm or dedicated biotechnology firm or do not undertake any biotechnology activities.

5.7 ANALYSIS OF EXPORT VALUES IN THE BIOECONOMY IN SOUTH AFRICA

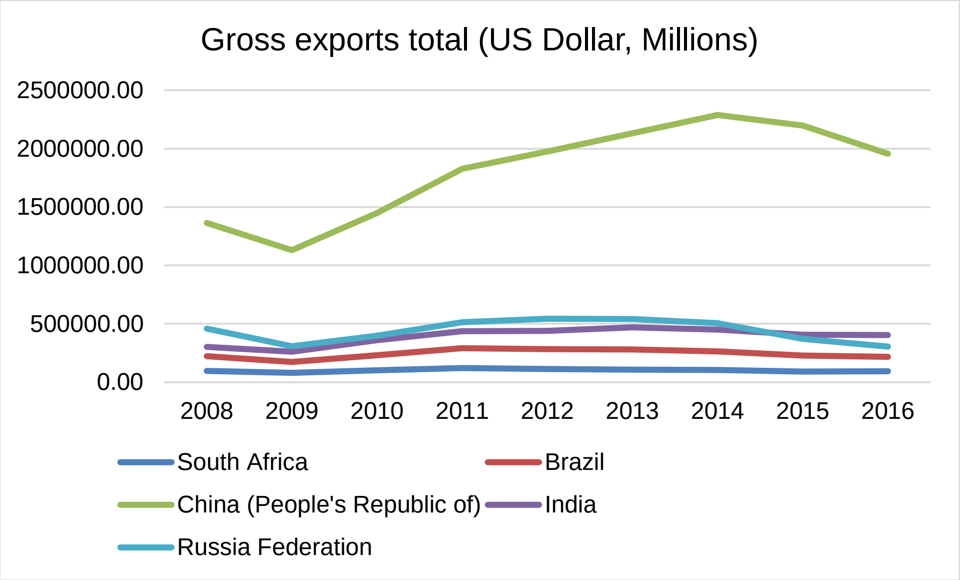

Figure 35: South African gross exports trends for all industries in comparison to other members of the BRICS

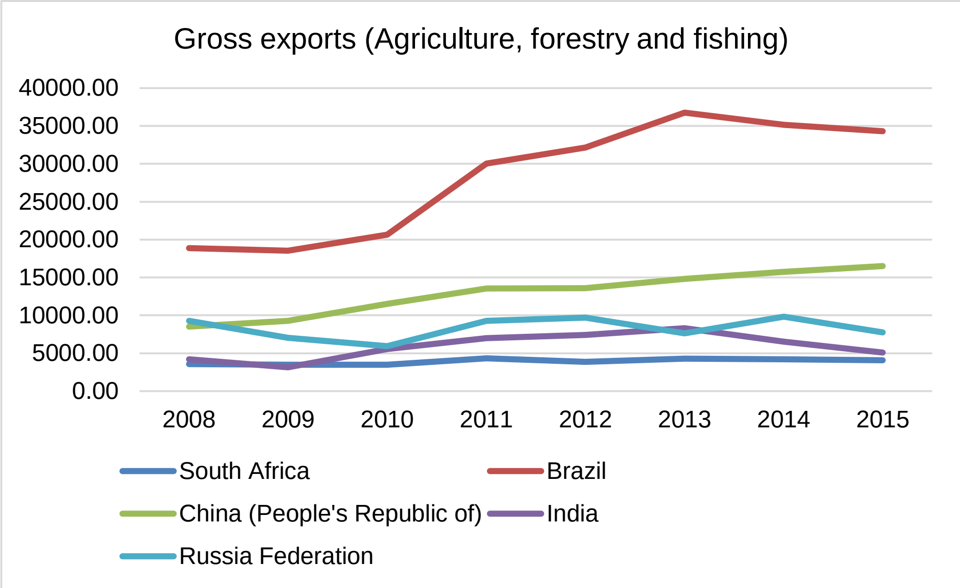

Figure 36: South African gross exports trends for agriculture, forestry and fisheries in comparison to other members of the BRICS

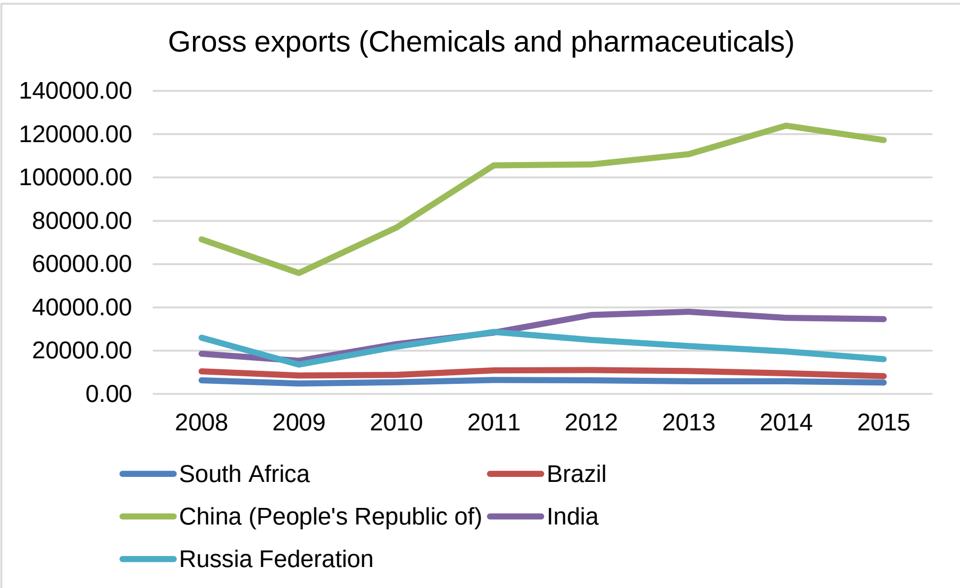

Figure 37: South African gross exports trends for chemicals and pharmaceuticals in comparison to other members of the BRICS

The analysis of gross exports totals for all industries (Fig. 35) shows that South Africa is relatively small compared to other members of the BRICS countries, and the observation is the same in agriculture, forestry and fisheries (Fig. 36), chemicals and pharmaceuticals (Fig. 37), and food products, beverages and tobacco (Fig. 38).

South Africa is relatively competitive for gross exports in wood and paper products (Fig. 39) and gross total for all industries in comparison with Russia, India and Brazil; and in comparison with Brazil and Russia in the chemicals and pharmaceuticals, and food products, beverages and tobacco. China recorded the highest gross exports for all industries in chemicals and pharmaceuticals, in food products, beverages and tobacco, and in wood and paper products, while Brazil recorded the highest gross exports in the agriculture, forestry and fisheries.

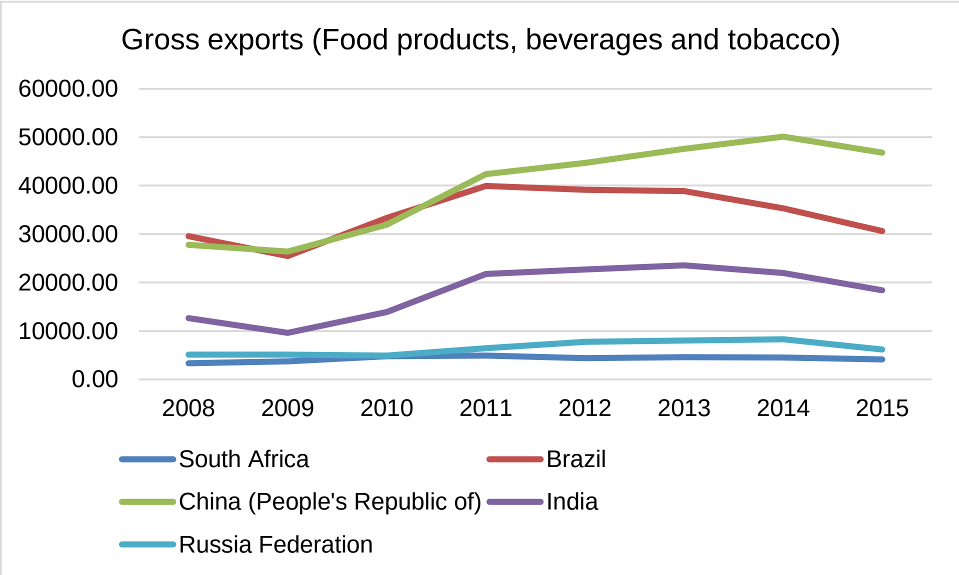

Figure 38: South African gross exports trends for food products, beverages and tobacco in comparison to other members of the BRICS

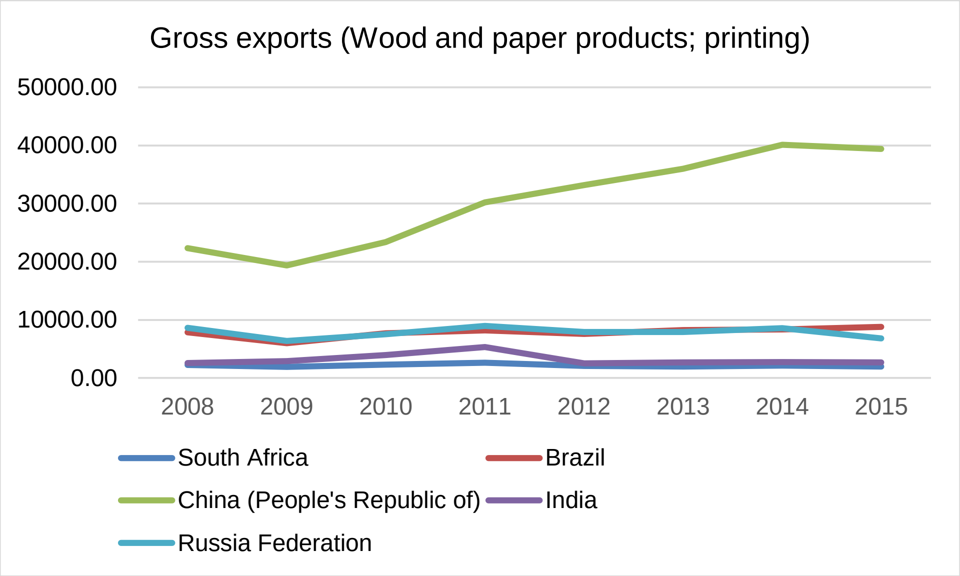

Figure 39: South African gross exports trends for wood and paper products in comparison to other members of the BRICS

In summary, the results indicate higher growth rates for resources committed for R&D in the bioeconomy compared to that of total research expenditures in South Africa. The growth rate in South Africa for researchers in headcounts in bioeconomy were low compared to the growth rates for researchers in headcounts across all fields. South Africa ranked last in the BRICS group in terms of the number of bioeconomy publications, patents and gross export total. The citations growth for South African bioeconomy publications were higher than Brazil, Russia and world citations during the period under review. The total patents citations for all BRICS members were inconsistent. There were 730 active firms in South Africa as of January 2021. Government departments, universities and bioeconomy funders were not included in the count. The practical application of the findings are discussed in Chapter 6.

CHAPTER 6: DISCUSSION

In this chapter discussions are drawn regarding the specific objectives of this study. These are bibliometric analysis and systematic review of literature on indicators; GERD, BERD and researchers in the bioeconomy; bibliometric analysis of bioeconomy research in South Africa; patentometric analysis of bioeconomy in South Africa; analysis of the number of active firms in the bioeconomy in South Africa; and analysis of export values in the bioeconomy in South Africa. The results from these objectives are explained and possible reasons and practical application of the findings are provided.

6.1 BIBLIOMETRIC ANALYSIS OF BIOECONOMY INDICATORS AND SYSTEMATIC REVIEW OF LITERATURE

This study observed that most researchers in the bioeconomy globally have interest on issues of production of biomass resources. For example, in the European Union the bioeconomy strategies focus on environmental sustainability and economic value chains based on existing waste-streams (Bugge et al., 2016). The environmental sustainability for instance, include indicators such as reduction in waste-streams of bio-resources and resource footprints which are instrumental in quantifying the resource and climate impact of the production and consumption system and the share of the bioeconomy. A clear hierarchy within the concept of sustainability is found where the environmental aspect dominates over economic and social indicators (Van Schoubroeck et al., 2018). Economic indicators are mainly focused on GDP, turnover and employment. According to the literature, these indicators are common in the bioeconomy (Wesseler and von Braun, 2017; Bracco et al., 2018; Wen et al., 2019). However, how these indicators should be measured for the bioeconomy is still not clear. It is suggested that the data for certain indicators should be collected from traditional statistics / national accounts in terms of number of companies, employees and sales in each industry sector of the bioeconomy, and so forth (BMEL, 2015; BMBF and BMEL, 2015). In most of the cases methodologies for data collection and assessment are not streamlined to assess the impact of the bioeconomy on these industry sectors. This leads to sparse information on impacts, along with data gaps, uncertainties, inaccuracies, lack of comparability of results and possible double-counting (FAO, 2018).

Ronzon and M'Barek (2018) propose the measure of value addition, such as labour productivity measure, as a set of socioeconomic indicators for the bioeconomy in the European Union in addition to GDP, turnover and jobs as calculated by the Joint Research Center (EC). Wesseler and von Braun (2017) propose two other approaches in measuring the bioeconomy, these are share of biobased products in the economy's products and services, and outcome measures such as reduced carbon emissions and sustainability of water, soil and biodiversity improvements. The former only serves intermediate purposes while the latter addresses issues of sustainability. However, outcome measures are complex to measure. Van Schoubroeck et al. (2018) proposes a framework for indicator selection using a stakeholder survey to obtain a prioritised list of sustainability indicators for biobased chemicals. The frameworks start by defining the goal and scope, followed by the development of a comprehensive list of indicators and stakeholder consultation. The last steps include multi-criteria analysis, proof of concept and a weighted set of indicators.

It is further observed that there are less publications that discuss knowledge and technological indicators for bioeconomy, such as the number of publications, patents and market share. Most of the knowledge and technological indicators in the bioeconomy still relies on studies or surveys conducted using the keyword "biotechnology". Therefore, more studies using keyword "bioeconomy" to study knowledge and technological indicators to measure growth of the bioeconomy are required. A more innovative and technologically advanced bioeconomy will be better able to grow output, employment, exports and attract investment.

There were no papers that focused on collaboration indicators which may be useful in distinguishing different stages and types of industry convergence in the bioeconomy (Sick et al., 2019). There is a further need for collaboration between countries to promote international agreements, collaborative research, regulatory systems, and market incentives, which may impact positively in the development of the bioeconomy (OECD, 2009a). Research is required to study the impacts of collaboration on outputs in the bioeconomy.

6.2 GERD, BERD AND THE NUMBER OF RESEACHERS IN THE BIOECONOMY IN SOUTH AFRICA

The results show that GERD in biotechnology in South Africa increased by a factor of 2.2 from 2008/09 to 2017/18, while GERD for total research increased by 1.8 fold. The BERD in biotechnology in South Africa increased by a factor of 2.7 during the same period, while BERD for total research increased by 1.3 fold. These indicate higher growth rates for resources committed to R&D in the bioeconomy compared to that of total research expenditures. The growth rate for researchers in headcounts in biotechnology are generally low compared to the growth rates for researchers in headcounts in all fields. However, at times when salaries increase, more GERD/BERD may not mean more researchers. As articulated in the New Growth Path (NGP), job opportunities exist in new economies such as the knowledge economy. The bio-economy is part of this knowledge economy where human capital development, specific skill sets and innovation are required. As such, the bioeconomy sector in South Africa needs to create more jobs. There may be a need to unpack the qualifications and training of the researchers in the bioeconomy. This could be accommodated by the number of FTE and/or percentage of researchers undertaking R&D in the bioeconomy with a tertiary qualification of master's degree or higher.

6.3 BIBLIOMETRIC ANALYSIS OF BIOECONOMY IN SOUTH AFRICA

This study provides a bibliometric analysis of bioeconomy research in South Africa and it discusses sources of growth in the country's bioeconomy publications. Since 2008, the research publications on bioeconomy in South Africa is increasing noticeably and is comparable with that of the BRICS countries. Although South Africa ranked last and 33rd in the world in terms of bioeconomy publication, the field appears to have taken off with 893 publications recorded in 2008 compared to 2572 in 2018. A paper by Pouris and Pouris (2009a) found the South African “average growth in biotechnology related publications to be 64% between 1995 to 2006”.

South African bioeconomy related publications in this study experienced a 188% growth rate as compared to 119% growth rate of bioeconomy world publications. In comparison to Brazil, Russia, India and China, South Africa needs to increase its research publications by a factor of 1.7, 4.8, 6.1 and 20 to produce an equivalent volume of knowledge production to Russia, Brazil, India and China respectively. In terms of total citations for period 2008 to 2015, over 95% of publications were cited. The citation growth during the period of 2008 to 2015 for South African bioeconomy related publications increased from 27,163 to 28,997; a 6.8% growth rate as compared to Brazil, Russia, India and China, which saw a growth rate of -6.29%, -12.2%, 11.5% and 69% respectively, and -25% of bioeconomy world citations. The South African bioeconomy research total citations trends recorded the highest citations in 2010 among the BRICS countries and the lowest in 2012. These discrepancies were observed in the BRICS group in general. South Africa needs to increase its total citations by a factor of 1.1, 3.5, 4.7 and 20 to produce an equivalent volume of quality knowledge to Russia, Brazil, India and China respectively.

The universities of Cape Town and Stellenbosch appear to be the main producers of bioeconomy publications in South Africa, followed by the universities of KwaZulu-Natal, Pretoria and Witwatersrand, with small differences in their publication profiles. The subject area Environmental Sciences Ecology is the most popular and the Journal PLoS One appears to be the main vehicle for reporting research results in the field of bioeconomy from South Africa. The collaboration profile for South Africa in the bioeconomy field appears to follow the same trend as South African scientific publications in terms of international collaboration, increasing from 48% in 2008 to 64% in 2018. This resulted in an increase in the quality of scientific output as the percentage of publications in the top 1% increased from 1.57% in 2008 to 2.15% in 2018. Bioeconomy publication collaborations within industry decreased from 1.46% in 2008 to 1.18% in 2018, which is a concern. Nationally, industry scientific collaborations increased, from 1.06% in 2007 to 1.35% in 2016 (NACI, 2018). There is a need for collaboration between universities and research institutes with the private sector to address the challenges of fragmentation in the bioeconomy and to ensure research undertaken at universities and research institutes is driven by market needs.

6.4 PATENTOMETRIC ANALYSIS OF BIOECONOMY IN SOUTH AFRICA

The results for this study show that the number of patents in biotechnology, pharmaceuticals, medical technology and environment-related technologies registered at the EPO and the USPTO that belong to South Africans are low compared to other BRICS members. The findings from the study are similar to observations in the literature based from other databases. A total of 58 biotechnology-related patents were awarded to South African inventors between 1976 and 2004 with majority belonging to non-South African entities (Cloete et al., 2006). From a study published by Patra and Muchie (2017), South Africa had about 638 biotechnology patents filed in WIPO in different classes of Biotechnology, the lowest among the BRICS. India produced 11763, China 29569, Brazil 1574 and Russia 4255 number of biotechnology patents. Between 2001 and 2014, a total of 194 biotechnology-related patents were produced by South Africa based on the WIPO database and whole count (Makhoba and Pouris, 2019a). South Africa had both the second lowest number of biotechnology patents among seven developing countries between 1991 and 2003 (Quach et al., 2006). According to Cloete et al (2006), the reason for the low number of biotechnology patents in South Africa could be the high costs associated with the registration in foreign patents. Therefore, several South Africans cannot afford to patent their IP internationally. Pouris and Pouris (2011) found that South African universities and academics applied for 280 patents in South Africa during the 1996-2006 period however only 58 of the 280 patents were protected in foreign patents. The high number of patents locally and few abroad is attributed to the costs associated with the registrations. Patents costs in South Africa is 20 to 30 times cheaper compared to foreign countries (Pouris and Pouris, 2011). This observation is similar nationally where South African inventors receive a relatively small number (91 in 2008 and 182 in 2019) of patents at the USPTO in all the technologies when compared to other countries (NACI, 2020). South Africa was ranked 30th in 2019 in terms of total number of patents granted at the USPTO for all technologies. Further, at the WIPO, between 2008 and 2020, the production of South African patents for all the technologies have been declining and according to NACI (2019), this trend is set to continue beyond 2020. South Africa recorded the highest number of patents at the EPO and USPTO in this study for all technologies investigated compared to Egypt and Nigeria. South Africa ranked number 1 in terms of patents awarded for African inventors by USPTO between 2000 and 2004 (Pouris and Pouris 2009b).

In this study, applications filed under the PCT, IP5 and triadic patent families and patent citations were used to distinguish between important patents and less influential patents among the BRICS members and to a certain extend, in comparison with Egypt and Nigeria. The use of multiple complementary indicators is important and provides comprehensive scenarios as articulated by Arts et al. (2013). The authors measured patent influence as the number of citations received by subsequent patents. Citations were distinguished across four domains identified by the industrial and organisational boundaries. Their results, based on an empirical analysis of 5671 biotechnology patents from 1976 to 2003, revealed that the contribution of the estimates to patent influence varies as the different domains of impact are considered. In this study, analyses show that South Africa does not need to improve on its patents quality by a large margin, as generally South African patents filed under the PCT, IP5 and triadic patent families are in proportion to its number of patents granted at the EPO and the USPTO. The observation is similar for other BRICS members. In terms of citations, South Africa generally improved on its citation counts and in most cases did not fall far behind Brazil and Russia. This could mean that the citation count is not necessarily a function of the number of patents filed or granted..

The important innovators of South African in the bioeconomy are mainly universities. Nationally, in terms of all the technologies at the USPTO, the observation is different, with the general patent grants by organisations mainly belonging to individuals, followed by private entities Sasol Technology and Amazon Technologies (NACI, 2018). This could mean research output by universities in the bioeconomy in South Africa is not readily translated to commercial products. Coordination of innovation efforts ensuring research at universities is industry-driven must be encouraged for the full realisation of the South Africa's Bioeconomy Strategy.

6.5 ANALYSIS OF THE NUMBER OF FIRMS IN THE BIOECONOMY IN SOUTH AFRICA

South Africa recorded 730 firms in the bioeconomy, compared to 78 and 106 biotechnology firms recorded from the 2007 and 2003 national biotechnology surveys respectively. The 2007 and 2003 surveys were limited to biotechnology firms and may have excluded organisations in the medical devices field, which contributes almost 30% of the number of firms identified in the bioeconomy in South Africa. The previous survey in 2007 consisted of the target population of 241 firms, however, the list was narrowed to 78 as being biotechnology active firms following e-mailed questionnaires. This means that a national survey to verify active bioeconomy firms is required. It is expected that the number of bioeconomy active firms identified in this study will be narrowed drastically once the identified firms are contacted to evaluate whether they fulfil the criteria for bioeconomy active firms. In comparison to the BRICS countries, Brazil recorded 160, 309 and 190 Biotechnology R&D firms in 2011, 2014 and 2017 respectively; an increase from 71 firms in 2007 (van Beuzekom and Arundel, 2009). The results mean that South Africa is performing well in terms of the number of firms in the bioeconomy when compared to Brazil. Therefore, South Africa does not need to expand its total firms output in the bioeconomy if compared to Brazil. Data for other members of the BRICS on active biotechnology or bioeconomy firms is not available on the OECD key biotechnology indicators database.

6.6 ANALYSIS OF EXPORT VALUES IN THE BIOECONOMY IN SOUTH AFRICA

The results show that the South African gross exports total for all industries in this study is relatively small compared to other BRICS members. For example, the analysis indicates that South African bioeconomy exports can be doubled in size without having to expand its total innovative products and production processes at the firm level to match that of Brazil in chemicals and pharmaceuticals, and wood and paper products. However, to produce an equivalent volume of bioeconomy exports to Brazil in the agriculture, forestry and fishing, and food products, beverages and tobacco industries, South Africa will require growth of its total innovative products and production processes at the firm level.

In summary, most papers discuss indicators of social, economic and environmental sustainability, yet there remains a gap as to how these interdependent sectors should be linked in order to develop a uniform methodology to measure all the aspects included in the bioeconomy. In terms of outputs measures, South Africa requires total growth of its bioeconomy innovation and technological outputs to match that of the other members of the BRICS. The resources committed to enhance innovation and technological change in the bioeconomy in South Africa must be improved, in particular, the number of researchers performing R&D in the bioeconomy.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

This chapter provides conclusions and recommendations from the six main objectives of the study: bibliometric analysis and systematic review of literature on indicators; GERD, BERD and researchers in the bioeconomy; bibliometric analysis of bioeconomy research in South Africa; patentometric analysis of bioeconomy in South Africa; analysis of the number of firms in the bioeconomy in South Africa; and analysis of export values in the bioeconomy in South Africa. The contributions and limitations of the study, as well as recommendations for other areas of future research are discussed in the following sections.

7.1 CONTRIBUTION

In terms of developing indicators for monitoring the implementation of the Bioeconomy Strategy in South Africa, the study firstly considered the literature in general on bioeconomy indicators to understand what publications perceive as important indicators for the bioeconomy. The results highlights that most publications discuss indicators of social, economic and environmental sustainability. Many countries, however, do not have the capacities to evaluate the socioeconomic and environmental impacts of technologies. From the literature selected, it is clear that one of the challenges in measuring the bioeconomy is that there is no uniform methodology developed to measure the bioeconomy. The measuring of the bioeconomy is still in its infancy and faces a number of methodological challenges (Wesseler and von Braun, 2017). As countries' grand challenges differ, there are no agreed upon indicators to measure the bioeconomy in order to assess the contribution of bioeconomy to the national economy (FAO, 2018). This means that countries' priorities must respond to the UN sustainable development goals to ensure alignment of priorities in the bioeconomy between countries. Further, bioeconomy cuts across many sectors and therefore cannot be treated like traditional sectors such as biotechnology or economics. Bioeconomy indicators should be based on multiple sources from different industry sectors of the bioeconomy (MOSTI and Bioeconomy Corporation, 2016). The analysis by

Bracco et al. (2018), based on research and surveys conducted in six countries (Argentina, Germany, Malaysia, The Netherlands, South Africa and United States), shows that the lack of a homogenous definition of bioeconomy across the six countries further contributes to the lack of a uniform methodology to measure bioeconomy indicators. The bioeconomy targets set by nation-wide strategies is dependent on countries' national priorities. The priorities should therefore align with the sustainable development goals to encourage uniform methodologies and should be measurable quantitatively, qualitatively or as aggregate indicators. There is a need for development of bioeconomy framework and indicators to measure bioeconomy contributions to the sustainable development goals. This will require coordination of programs within and among role players in the bioeconomy sectors, within or between countries, and the establishing protocols for the sharing of data to implement a single harmonised bioeconomy indicators framework and report, allowing the monitoring and measuring of all the industry sectors included in the bioeconomy.

The literature on bioeconomy is still scattered around many subjects, however, the majority of the publications discovered in this study were on environmental and related sciences and Journal Cleaner Production. In terms of indicators, most publications were from Journals Sustainability and Amfiteatru Economic, however, the relevant information for the analysis was gathered from official bioeconomy strategies documents or were of a technical nature and not official statistics. In the absence of official statistics reporting on indicators of the bioeconomy, literature is partly based on proposed or estimated indicators. The proposed or estimated indicators presented may be subject to correction in the future when the actual data becomes available. Emerging economies generally emphasise developmental issues such as jobs, employment and share of GDP, while emerged economies focus on outcome measures such as reduction in carbon emissions and sustainability of resource footprints in their bioeconomy strategies.

Based on the literature reviewed, the bioeconomy can be defined as a bio-based multi-sectoral system that addresses economic, environmental, technological and social challenges by contributing to the UN sustainable development goals. The bioeconomy is already making sustainable contribution on issues such as availability and share of biomass as renewable raw materials and production of cleaner products in primary and secondary sectors. All the sectors in the bioeconomy must be interconnected, and countries' bioeconomy priorities must respond to UN sustainable development goals in order to develop a uniform methodology to measure the bioeconomy (Lokko et al., 2018).

The South African bioeconomy strategy identified several potential indicators as elements of a bioeconomy measurement framework. As indicated by the NACI, the strategy did not clearly articulate the measurement framework to monitor the implementation of the strategy. The NACI proposed a set of indicators that could be used for monitoring of the strategy. Among those indicators proposed are the innovation indicators developed in this study; that is the measure of the number of South African bioeconomy authored publications and the citations (science outputs), the measure of the number of South African bioeconomy patents and the citations at the EPO and USTPO (technology outputs), and the number of bioeconomy firms in South Africa and the value of their exports as an estimate of innovation by firms (economic outputs).

The findings contribute to the measurement and assessment of the progress of innovation in bioeconomy in South Africa. Indicators related to resources based on expenditure and researchers committed to R&D in the bioeconomy were developed. Indicators related to resources based on the provision and establishment of equipment and infrastructure, and on coordinating networks must be investigated to complete input measures for the bioeconomy in South Africa. A comparison of the changes in input as compared to changes in output over time can provide evidence on the structure and productivity of national innovation systems (OECD, 2016). However, productivity is not always a function of resources available. Makhoba and Pouris (2019) found that South Africa had the highest R&D efficiency in biotechnology using both patents and publications as indicators, however, South Africa had limited resources compared to the BRICS countries. Further, input-output analysis methods can provide information about the size of the bioeconomy (Budzinski et al., 2017; Zeug et al., 2019). If outputs grow more rapidly than inputs, the efficiency is increasing and so is the size of the bioeconomy.

During the period under investigation, the research publications on bioeconomy in South Africa increased noticeably and was comparable with that of the BRICS countries. Since the launch of the bioeconomy strategy, the average growth of South African bioeconomy related publications increased three-fold. For example, the analysis in this study indicates that the bioeconomy research system can be doubled in size without having to expand the total research system to match that of Russia's bioeconomy related publications. However, to produce an equivalent volume of bioeconomy knowledge production to Brazil, India and China, South Africa will require growth of the total research system. The citations growth for South Africa's bioeconomy publications increased during this period and was higher than Brazil, Russia and world citations growth. This shows that South African bioeconomy related publications are generally of high quality. The concern, however, is that South Africa experienced a decline in bioeconomy industry collaboration publications during this period. There needs to be incentives in place to encourage collaboration between research institutions and the private sector in the bioeconomy in South Africa.

In terms of patents, South Africa's patenting activities in bioeconomy remained relatively low. The total citations for all BRICS members generally decreased, although the growth rates were inconsistent. South Africa requires a total expansion of its bioeconomy patenting activities to encourage and enhance innovation and technological advancements in this field. To produce an equivalent volume of bioeconomy patents to Brazil, Russia, India and China at the EPO and the USPTO, South Africa requires substantial growth of its total bioeconomy patenting activities. The important innovators of South Africa in this field are mainly universities and public research institutions as compared to other members of the BRICS. Incentives that encourage collaboration between research institutions and local innovation firms are required for the full realisation of South Africa's Bioeconomy Strategy.

The high bioeconomy publication trends and the low bioeconomy patenting activities in South Africa observed in this study could further mean that, aside from funding availability, there is increased fragmentation between government, tertiary education and business enterprises in the area of bioeconomy in South Africa. It would appear that the most prominent way of improving the situation is through collaborative research. The Bioeconomy Strategy in South Africa encourages research in academia that is industry-driven to encourage collaboration between academia and industry. Therefore, it is recommended that government, together with the business sector, set bioeconomy research priorities and that the higher education sector, including the science councils, respond to such priorities to encourage collaboration across the value chain. Government should direct its funding for research towards academia and industry should up-scale the research outputs from academia. This in particular may encourage research institutions to undertake R&D with national and market demands, and thus improve government-industry partnerships and patenting activities in the bioeconomy.

South Africa's Bioeconomy Strategy funding model for research in academia and research institutions should be based on the availability of an identified commercial partner and on priorities set by government and industry. In South Africa, during 2017/18, 4.2% and 2.2% of business-funded R&D supported the higher education sector and science councils respectively. A large proportion of government-funded R&D supported the higher education sector (58.0%) and the science councils (29.4%) (DSI, 2019). In order to reduce the possible fragmentation, all role players must collaborate and share the resources to achieve the goals of the Bioeconomy Strategy. According to the NDP (NDP, 2012), research and innovation by universities, science councils, government and the business sector have key roles to play in improving South Africa's global competitiveness. Coordination between these different role players is suggested as one of the fundamental issues needing attention.

There is a further need for collaboration between countries, to promote international agreement, collaborative research, the sharing of IP, regulatory systems, and market incentives for the use of biotechnology products, processes and services (OECD, 2009a). The increase in South African scientific publications is driven partly by the increase in international research collaborations (NACI, 2018). The study showed that international collaboration between South Africa and other countries in bioeconomy research is above the national average. It is, however, not clear whether there were co-authored publications between South African industry and international industry. The study did not look at such relationships, since the paper's focus was on the growth of bioeconomy in South Africa. Such industry to industry relationships may be important, for example, if South Africa is to improve its patenting capabilities in the bioeconomy.

R&D resources from government and the business sector must also be channelled for such collaborative research. In South Africa, proportional foreign-funded R&D by sector in 2017/18 was the highest in the higher education (38.3%) followed by the not-for-profit organisations (22.0%). Government and the business sector received 12.0 % and 12.1% of foreign funding for R&D respectively (DSI, 2019). It appears that South African government must establish an instrument to attract foreign investment in R&D in the bioeconomy for the government and business sectors. The NFF for higher education institutions is an example of such an instrument. Such a global perspective on co-authored publications among industries and governments will be crucial in monitoring collaboration between South Africa and other global partners. This may inter alia increase the benefits of the bioeconomy by increasing the number of resources, in addition to local resources, in bioeconomy and focusing on specific issues of the developing and/or developed world. This may allow for free trade in bioeconomy products and performance standards to support environmental sustainability, i.e. through carbon trading systems or environmental taxes, amongst others. Co-authored research publications are also important indicators for sectoral or inter-sectoral collaborations. More research needs to be done to study the impacts of co-authored publications on patenting activities and commercialisation outputs in the bioeconomy.

The findings of this study have a number of policy implications. With a dedicated Bioeconomy Strategy in place in South Africa, it means that funding for knowledge production under the Strategy must be further increased. The funding must come from both the government and business sector through public-private collaborations. With the current outbreak of a pandemic, it seems that there will be an opportunity for increased availability of resources, in particular, on health related topics, indigenous knowledge systems, and food and nutrition research, among others, to reduce the long term burden of the pandemic. All these sectors are covered under the bioeconomy, however, budget availability is not obvious.

Therefore, with the possible limitation of available resources for the bioeconomy in South Africa, other mechanisms to encourage knowledge production in the sector must be investigated.

Furthermore, the low level of patenting activities in bioeconomy in South Africa is similar to that of all the technologies in South Africa. This means that funding instruments dedicated to all technological innovation must be put in place. According to NACI (2017), the decline in the number of South African patents may be due to more government incentives put in place on scientific publications. This may well be encouraging researchers in South Africa to publish rather than invent. Further, with the closure of the Innovation Fund in South Africa, South African innovators only rely on the National Intellectual Property Management Office incentives for intellectual property creators and commercialising. The incentive is not successful in bridging the gap between the need for innovation and the lack of resources available to make it happen.

The White Paper on Science, Technology and Innovation in South Africa (DST, 2019) emphasises the need for state procurement of innovation, local consumption of domestic innovative products and the establishment of public-private collaborations to encourage innovation. The challenge that is highlighted is the cultivation of a culture of slightly prioritising science, technology and innovation in the country and integrating it into government planning and budgeting at the highest level. The government of South Africa is expected to set up a sovereign innovation fund to leverage investment by the public and private sectors to address gaps in technology advancements. The fund will be designed to complement and enhance existing funding instruments and to provide funding on a larger scale for the development and maturation of radical innovations and emerging industries. The deficiency in South Africa is that science, technology and innovation does not receive priority compared to other sectors of government. This is due to the challenges of poverty, inequality, unemployment, education, crime and underdeveloped health system etc., which receive first priority from government. The availability of funds to accelerate technology innovation in the country may therefore be of lower priority.

The number of firms in the bioeconomy increased drastically since the last survey in 2007, however, there is a need for a survey to identify active firms from the data extracted that fulfil the criteria as undertaking bioeconomy activities. This should include the analysis of the expenditure and turnover generated by innovative products and production processes to measure the impact the bioeconomy firms have in terms of the contribution to innovation in the bioeconomy. In this study, however, exports were used to provide estimates of innovation at the firm level and the results showed that South Africa requires growth of its total innovative products and production processes to match that of the other BRICS countries.

The resources committed to the bioeconomy in South Africa during the period investigated showed higher growth rates compared to that of total research expenditures for all scientific fields. The results indicate that South Africa does not need to increase its resources devoted to R&D in the bioeconomy, except for collaborative purposes, compared to that of total research expenditures nationally. At times, if salaries increase, more GERD may not mean more researchers. Indeed, the growth rate for researchers in headcounts in biotechnology are low compared to the growth rates for researchers in headcounts in all fields. There is a need to increase the number of researchers in the bioeconomy. There may be a need to unpack the qualifications and training of the researchers in the bioeconomy. This could be accommodated by the number of FTE and/or percentage of researchers undertaking R&D in the bioeconomy with tertiary qualifications of a master’s degree or higher.

7.2 LIMITATIONS AND FUTURE RESEARCH

The lack of an internationally accepted uniform methodology to measure the bioeconomy remains a gap. Therefore, the measure of progress of the South African Bioeconomy Strategy in comparison with other countries with bioeconomy strategies remains a challenge. The South African Bioeconomy Strategy aims to make a significant contribution to South Africa’s GDP by 2050. The NACI recommended indicators for measuring, evaluating and monitoring the South African bioeconomy at both the sectoral-wide and economy-wide level. These are

GDP, turnover, sales, employment, exports, investment and innovation. This doctoral study provides a number of innovation and exports performance indicators for the bioeconomy. This study also details the data used to construct each of these performance indicators and the outcomes thereof. However, as with many scientometrics studies, there are shortcomings in this study.

The bioeconomy share of national GDP, turnover and sales for growth measures, investments in terms of GFCF, and the number of jobs in the bioeconomy still need to be measured. These are the economy-wide level indicators that are recommended by NACI. These indicators measure the socio-economic impact of the bioeconomy and were considered to fall outside of the scope of this study, which focusses on science, technology and innovation indicators for the bioeconomy. However, in order to provide the complete set of indicators for the bioeconomy as recommended by NACI, data on the socio-economic indicators must be collected.

Countries comparative analysis in R&D within BRICS context generaly is difficult. South Africa with a population of just over 50 million, is too small as an economy to compete with other members of the BRICS. Nonetheless, countries comparative analysis within BRICS context remain relevant from a policy perspective. The BRICS countries are considered five major emerging national economies, and the countries have been working towards closer cooperation between the members in various scientific disciplines. Therefore, a benchmark amongst these countries is a fair comparison. However to improve this comparative analysis within BRICS context, other countries such as Mexico and South Korea which have recently shown solid economic growth as with BRICS, should be investigated for comparative analysis in future research.

In terms of the innovation indicators provided in this study, the business innovation survey on bioeconomy firms is required to complete the innovation indicators and provide accurate data on the number of firms that fulfil the criteria for being bioeconomy active and to measure expenditures and turnover generated by their innovative products and production processes. It is recommended that such surveys be conducted every 5 years and that data is provided to the OECD for countries comparison purposes. The DSI needs to allocate funds for such a survey.

Data for statistics purposes is classified by scientific field or technology or industrial sectors. There is a need to identify scientific fields or technologies or specific industrial sectors of the bioeconomy to provide accurate measurements instead of proxies. The challenge for bioeconomy measurements is that most sectors of the bioeconomy, such as chemicals, textiles, rubbers, plastics and others, are not 100% bio-based economic sectors. The specification needs to be investigated by measurement experts and/or subject matter experts with specific knowledge of value chains to adjust these further, to avoid under-counting or over-counting indicators for the bioeconomy. How this should be done is a challenge.

Finally, as the bioeconomy concept is developed in South Africa, indicators that focus on outcome measures, such as reduction in carbon emissions and sustainability of resource footprints etc., will have to be measured to advance South Africa’s Bioeconomy Strategy to focus on specific issues affecting the developed world. South Africa’s Bioeconomy Strategy is based on the OECD bioeconomy definition that is technology driven. Therefore, the indicators proposed for the Bioeconomy Strategy of South Africa and those developed in this study focus mainly on developing bio-based technologies rather than measuring the contribution of the bioeconomy to green growth and sustainability, as it is seen with the developed world. The bio-based technologies approach paints the bioeconomy as a biotechnology subsector while the green growth and sustainability approaches consider biomass availability, the sustainability of its cultivation, and biotechnology as one of many technologies employed in the bioeconomy system (Befort 2020).

REFERENCES

Abramo, G., D'Angelo, C. A., and Cicero, T. (2012). What is appropriate length of the publication period over which to assess research performance? *Scientometrics*, 93(3), 1005-1017.

Abrams, D.S., and Sampat, B.N. (2017). What's the value of patent citations? Evidence from pharmaceuticals. Accessed 25 November 2019, http:www.law.northwestern.edu/events.

Academy of Science of South Africa (ASSAf). (2009). Consensus report on revitalising clinical research in South Africa. Pretoria. Accessed 20 February 2020, https://www.assaf.org.za.

Agency Inovasi Malysia (AIM). (2013). National Biomass Strategy 2020: New wealth creation for Malaysia's biomass industry, 2. *Agency Inovasi Malysia*. Accessed 15 March 2019, http://www.a`nbs220.gov.my.

Aguilar, A., Twardowski, T., and Wohlgemuth, R. (2019). Bioeconomy for Sustainable Development. *Biotechnology Journal*, 14(8), doi: 10.1002/biot.201800638.

Aguillo, I. (2012). Is Google Scholar useful for bibliometrics? A webometric analysis. *Scientometrics*, 91(3), 343–351.

Albert, M.B., Avery, D., Narin, F., and McAllister, P. (1991). Direct validation of citation counts as indicators of industrially important patents. *Research Policy*, 20(3), 521-543.

Alcácer, J., Gittelman, M., and Sampat, B. (2009). Applicant and Examiner Citations in US Patents: An overview and analysis. *Research Policy*, 38(2), 415-427, https://doi.org/10.1016/j.respol.2008.12.001.

Anghel, I., Simincă, M., Cristea, M., Sichigea, M., Noja, G. G. (2018). Intellectual capital and financial performance on biotech companies in the pharmaceutical industry. *Amfiteatru Economic*, 20(49), 631-646.

Arts, S., Appio, F.P., and Van Looy, B. (2013). Inventions shaping trajectories: do existing patent indicators provide a comprehensive picture? *Scientometrics*, 97, 397-419, doi: 10.1007/s11192-013-1045-1.

Asanda, R., and Stern, T. (2018). Competitive Bioeconomy? Comparing Bio-based and Non-bio-based Primary Sectors of the World. *Ecological Economics*, 149, 120-128. https://doi.org/10.1016/j.ecolecon.2018.03.014.

Aylward, D. K. (2004). Innovation-export Linkages within Different Cluster Models: A Case Study from the Australian Wine Industry. *Prometheus*, 22 (4), 423-37.

Bajwa, R. S., and Yaldram, K. (2013). Bibliometric analysis of biotechnology research in Pakistan. *Scientometrics*, 95, 529 - 540.

Balconi, M., Brusoni, S., and Orsenigo, L. (2010), In Defence of the Linear Model: An Essay, *Research Policy*, 39, 1-13. doi:10.1016/j.respol.2009.09.013

Bambo, T.L., and Pouris, A. (2020). Bibliometric analysis of bioeconomy research in South Africa. *Scientometrics*, 125, 29-51, doi: 10.1007/s11192-020-03626-y.

Banerjee, P., Gupta, B. M., and Garg, K. C. (2000). Patent statistics as indicators of competition - an analysis of patenting in biotechnology. *Scientometrics*, 47, 95-116.

Barnabé, M. A., Gordon, R., Ramjee, G., Loots, G., and Blackburn, J.M. (2020). National expenditure on health research in South Africa: How has the landscape changed in the past decade? *South African Medical Journal*, 110(4), 274-283. https://doi.org/10.7196/SAMJ.2020.v110i4.14349

Barragán-Ocaña, A., Gómez-Viquez, H., Merritt, H., and Oliver-Espinoza, R. (2019). Promotion of technological development and determination of biotechnology trends in five selected Latin American countries: An analysis based on PCT patent applications. *Electronic Journal of Biotechnology*, 37, 41-46, https://doi.org/10.1016/j.ejbt.2018.10.004.

Bartolini, F., Gava, O., Brunori, G. (2017). Biogas and EU's 2020 targets: Evidence from a regional case study in Italy. *Energy Policy*, 109, 510-519.

Befort, N. (2020). Going beyond definitions to understand tensions within the bioeconomy: The contribution of sociotechnical regimes to contested fields. *Technological Forecasting and Social Change*, 153, 119923. https://doi.org/10.1016/j.techfore.2020.119923.

Bejinaru, R., Hapenciuc, C. V., Condratov, I., Stanciu, P. (2018). The university role in developing the human capital for a sustainable bioeconomy. *Amfiteatru Economic,* 20(49), 583-598.

Bessen, V. (2008). The value of U.S. patents by owner and patent characteristics. *Research Policy*, 37(5), 932-945, https://doi.org/10.1016/j.respol.2008.02.005.

Biber-Freudenberger, L., Basukala, A. K., Bruckner, M., and Börner, J. (2018). Sustainability Performance of National Bio-Economies. *Sustainability*, 10, 2705; doi:10.3390/su10082705.

Bioeconomy Council. (2018). Global Bioeconomy Summit 2018; Conference Report; Federal Ministry for Education and Research: Bonn, Germany. Accessed on 23 August 2019, http:// www.gbs2018.com.

Blanc, S., Massaglia, S., Brun, F., Peano, C., Mosso, A., and Giuggioli, N.R. (2019). Use of Bio-Based Plastics in the Fruit Supply Chain: An Integrated Approach to Assess Environmental, Economic, and Social Sustainability. *Sustainability*, 11, 2475; doi:10.3390/su11092475.

Böcher, M., Töller, A.E., Perbandt, D., Beer, K., and Vogelpohl, T. (2020). Research trends: Bioeconomy politics and governance. *Forest Policy and Economics*, 118, doi: 102219 https://doi.org/10.1016/j.forpol.2020.102219

Boë, L-J., Berthommier, F., Legou, T., Captier, G., Kemp, C., Sawallis, T.R., Becker, Y., Rey, A., and Fagot, J. (2017). Evidence of a Vocalic Proto-System in the Baboon (Papio papio) Suggests Pre-Hominin Speech Precursors. *PLoS ONE*, https://doi.org/10.1371/journal.pone.0169321.

Bordoloi, J., and Dekah Boruah, H.P. (2018). Analysis of Recent Patenting Activities in the Field of Bioremediation of Petroleum Hydrocarbon Pollutants Present in the Environment, *Recent Patents on Biotechnology*, 12(1), 3-20, doi: 10.2174/1872208311666170504111019.

Bornmann, L., Wagner, C.S., and Leydesdorff, L. (2015). BRICS countries and scientific excellence: A bibliometric analysis of most frequently-cited papers. *Journal of the Association for Information Science and Technology*, 66 (7), 1507–1513. https://doi:10.1002/asi.23333.

Borrás, S., and Edquist, C. (2013). The choice of innovation policy instruments. *Technological Forecasting and Social Change*, 80 (8), 1513–1522.

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

Budzinski, M., Bezama, A., and Thrän, D. (2017). Monitoring the progress towards bioeconomy using multi-regional input-output analysis: The example of wood use in Germany. *Journal of Cleaner Production*, 161, 1-11.

Bugge, M. M., Hansen, T., and Klitkou, A. (2016). What is the Bioeconomy? A review of the literature. *Sustainability*, 8, 691.

Bull, A.T., Holt, G., and Lilly, M. D. (1982). Biotechnology. International Trends and Perspectives. *Organisation for Economic Cooperation and Development.* Accessed 15 March 2019, http://www.oecd.org/sti/emerging-tech/2097562.pdf.

Busu, C., and Busu, M. (2018). Economic modelling in the management of transition to bioeconomy. *Amfiteatru Economic,* 21(50), 24-40.

Callaert J., Van Looy, B., Verbeek, A., Debackere, K., and Thijs, B. (2006), Traces of Prior Art: An Analysis of Non-Patent References Found in Patent Documents, *Scientometrics*, 69(1), 3-20.

Carpenter, M. P., Narin, F., and Woolf, P. (1981). Citation rates to technologically important patents. *World Patent Information*, 3(4), 160-163.

Carpenter, M., and Narin, F. (1983). Validation study: Patent citations as indicators of science and foreign dependence. *World Patent Information*, 5(3), 180-185.

Chadha, A. (2009). Product Cycles, Innovation, and Exports: A Study of Indian Pharmaceuticals. *World Development*, 37(9),1478-83.

Chavarria, H., Trigo, E., Villarreal, F., Elverdin, P., Piñeiro, P. (2020). Bioeconomy: A sustainable development strategy. *Sustainable Energy, Water and Food Systems*. G20 Insight. https://www.g20-insights.org/wp-content/uploads/2020/11/T20_TF10_PB18.pdf

Chekol, C., and Gebreyohannes, M. (2018). Application and current trends of biotechnology: a brief review. *Austin Journal of Biotechnology and Bioengineering*, 5(1), 1088.

Chen, Z., and Guan, J. (2011). Mapping biotechnology patents of China from 1995-2008. *Scientometrics*, 88, 73-89.

Choi, C., and Park, Y. (2009). Monitoring the organic structure of technology based on the patent development paths. *Technological Forecasting and Social Change*, 76(6), 754-768.

Cîrstea, S. D., Cîrstea, A., Popa, I. E., and Radu, G. (2019). The role of bioenergy in transition to a sustainable bioeconomy – study on EU countries. *Amfiteatru Economic,* 21(50), 75-89. DOI: 10.24818/EA/2019/50/75.

Cloete, T. E., Nel, L.H., and Theron, J. (2006). Biotechnology in South Africa. *TRENDS in Biotechnology*, 24 (12), 557-562. doi:10.1016/j.tibtech.2006.10.009.

Comanor, W.S, and Scherer, F. M. (1969). Patent Statistics as a Measure of Technical Change. *Journal of Political Economy*, 77(3), 392-398. https://doi.org/10.1086/259522.

Connolly, R.A., and Hirschey, M. (1988). Market value and patents. *Economics Letters*, 27, 83-87.

Cooper, R.G. (1990). Stage-gate systems: a new tool for managing new products. *Business Horizon*, 33 (3), 44–54.

Cristóbal, J., Matos, C. T., Aurambout, J. P., Manfredi, S., and Kavalov, B. (2016). Environmental sustainability assessment of bioeconomy value chains. *Biomass and Bioenergy*, 89, 159-171.

Crosby, M. (2007). Patents, Innovation and Growth. *Economic Record*, 76 (234), 255-267. https://doi.org/10.1111/j.1475-4932.2000.tb00021.x.

Dalpé, R. (2002). Bibliometric analysis of biotechnology. *Scientometrics*, 55(2), 189-213.

Dash Nelson, G., and Rae, A. (2016). An Economic Geography of the United States: From Commutes to Megaregions. *PLoS ONE*, https://doi.org/10.1371/journal.pone.0166083.

de Solla Price, D. (1983). Sealing wax and string: A philosophy of the experimenter's craft and its role in the genesis of high technology. Paper presented at the Sarton Lecture, AAAS Meeting (May 1983).

Dehdarirad, T., Sotudeh, H., and Freer, J. (2019). Bibliometric mapping of microbiology research topics (2012–16): a comparison by socioeconomic development and infectious disease vulnerability values. *FEMS Microbiology Letters*, 366, doi: 10.1093/femsle/fnz004.

DeLooze, M.A. (1994). The application of scientometric tools to the analysis of a sector in plant biotechnologies: nitrogen fixation. *Scientometrics*, 30, 23-34.

DeLooze, M.A., and Lemarié, J. (1997). Corpus relevance through co-word analysis: an application to plant proteins. *Scientometrics*, 39(3), 267-280.

DeLooze, M.A., and Ramani, S.V. (1999). Biotechnology patent applications in Europe – A look at the difference between French, British, and German patent application trends. *Nature Biotechnology*, 17, 83-85.

DeLooze, M.A., Coronini, R., and Joly, P. B. (2001). A note on recent trends in knowledge creation and appropriation through genomics: a scientometric analysis. *International Journal of Biotechnology*, 3, 4-22.

Department of Arts, Culture, Science and Technology South Africa (DACST). (1996). White Paper on Science and Technology: Preparing for the 21st Century. *Government of the Republic of South Africa*. Pretoria Government Printer. Accessed 12 March 2019, https://www.gov.za/sites/default/files/gcis_document/201409/sciencetechnologywhitepaper.pdf.

Department of Arts, Culture, Science and Technology South Africa (DACST). (1999). National Research and Technology Foresight. *Government of the*

Republic of South Africa. Pretoria. Accessed 12 March 2019, https://www.dst.gov.za/index.php/resource-center/foresight-reports.

Department of Planning, Monitoring and Evaluation (DPME). (2016). Development Indicators. https://www.dpme.gov.za/publications/Reports%20and%20Other%20Information%20Products/Development%20Indicators%202016.pdf (Accessed 10 May 2019).

Department of Science and Innovation (DSI). (2019). South African National Survey of Research and Experimental Development. Statistical reports 2017/18. *Government of the Republic of South Africa*. Produced by the Human Sciences Research Council's Centre for Science, Technology and Innovation Indicators (HSRC-CeSTII) on behalf of the Department of Science and Innovation. Pretoria. Accessed 23 January 2020, http://www.dst.gov.za/index.php/resource-center/rad-reports.

Department of Science and Innovation (DSI). (2021). South African National Survey of Research and Experimental Development. Statistical reports 2018/19. Produced by the Human Sciences Research Council's Centre for Science, Technology and Innovation Indicators (HSRC-CeSTII) on behalf of the Department of Science and Innovation (DSI). Pretoria. Accessed 19 March 2021, http://www.dst.gov.za/index.php/resource-center/rad-reports.

Department of Science and Technology (DST). (2001). National Biotechnology Strategy for South Africa. *Government of the Republic of South Africa*. Pretoria. Accessed 12 March 2019, http://www.gov.za/documents/national-biotechnology-strategy-south-africa.

Department of Science and Technology (DST). (2003). Audit of the South African biotechnology sector. eGoliBio Life Sciences Incubator. *Government of the Republic of South Africa*. Pretoria. Accessed 12 March 2019, https://www.oecd.org/sti/inno/33706873.pdf.

Department of Science and Technology (DST). (2007a). Towards 2018: South Africa’s 10-Year National Innovation Plan. Government of the Republic of South Africa. Pretoria. Accessed 12 March 2019. http://www.sagreenfund.org.za/wordpress/wp-content/uploads/2015/04/10-Year-Innovation-Plan.pdf

Department of Science and Technology (DST). (2007b). National Biotechnology Audit. Biotechnology use and development in South Africa. Government of the Republic of South Africa. Pretoria. Accessed 12 March 2019, https://www.gov.za/sites/default/files/gcis_document/201409/national-biotech-audit0.pdf.

Department of Science and Technology (DST). (2012). Department of Science and Technology Ministerial Review Committee on the Science, Technology and Innovation landscape in South Africa. Final Report. *Government of the Republic of South Africa*. Pretoria. Accessed 12 March 2019, https://www.dst.gov.za/images/FINAL_MINISTERIAL_REPORT_MAY_16__4_.pdf.

Department of Science and Technology (DST). (2013). The Bio-Economy Strategy. *Government of the Republic of South Africa*. Pretoria. Accessed 12 March 2019, http://www.gov.za/sites/default/files/gcis_document/201409/bioeconomy-strategya.pdf.

Department of Science and Technology (DST). (2019). White Paper on Science, Technology and Innovation as government policy. *Government of the Republic of South Africa*. Pretoria. Accessed 31 May 2020, https://www.dst.gov.za/images/2019/WHITE_PAPER_ON_SCIENCE_AND_TECHNOLOGY_web.pdf.

Dietz, T., Börner, J., Förster, J., and von Braun, J. (2018) Governance of the bioeconomy: a global comparative study of national bioeconomy strategies, *Sustainability*, 10 (9), 3190, https://doi.org/10.3390/su10093190.

Djordjevic, B. J., Djordjevic, G., Cerovic, S., Alcakovic, S., and Djokovic, F. (2018). Knowledge-based bioeconomy: The use of Intellectual Capital in food industry of Serbia. *Amfiteatru Economic,* 20(49), 717-731.

Dosso, M, Martin, B. R., and Moncada-Paternò-Castello, P. (2008). Towards evidence-based industrial research and innovation policy. *Science and Public Policy*, 45 (2), 143–150.

Duquenne, M., Prost, H., Schöpfel, J., and Dumeignil, F. (2020). Open Bioeconomy – A Bibliometric study on the accessibility of articles in the field of Bioeconomy. *Publications*, 8, 55; doi:10.3390/publications8040055.

Dziallas, M and Blind, K. (2019). Innovation indicators throughout the innovation process: An extensive literature analysis. *Technovation*, 80–81, 3–29. https://doi.org/10.1016/j.technovation.2018.05.005.

Edler, J., Fagerberg, J. (2017). Innovation policy: what, why, and how. *Oxford Review of Economic Policy*, 33 (1), 2–23.

Efken, J., Dirksmeyer, W., Kreins, P., Knecht, M. (2016). Measuring the importance of the bioeconomy in Germany: Concept and illustration. *NJAS-Wageningen Journal of Life Sciences*, 77, 9-17. https://doi.org/10.1016/j.njas.2016.03.008.

Egenolf, V., and Bringezu, S. (2019). Conceptualization of an indicator system for assessing the sustainability of the bioeconomy, *Sustainability*, 11 (2), 443, https://doi. org/10.3390/su11020443.

Elango, B., and Rajendran, P. (2017). Whole counting vs. whole-normalized counting: a country level comparative study of internationally collaborated papers on Tribology. *International Journal of Information Dissemination and Technology*, 7 (2), 123–127, https://doi.org/10.5958/2249-5576.2017.00010.3.

European Commission (EC). (2012). Innovating for Sustainable Growth: A Bioeconomy for Europe. Brussels. *Europa*. Accessed 23 June 2019, Available from: https://publications.europa.eu/en/publication-detail/publication/1f0d8515-8dc0-4435-ba53-9570e47dbd51.

Eurostat. (2018). Patent statistics background: Statistics Explained. Accessed 19 August 2019, http://ec.europa.eu/eurostat/statisticsexplained.

Falagas, M.E., Pitsouni, E.I., Malietzis, G.A., and Pappa, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. *The FASEB Journal*, 22(2), 338-342.

Falcone, P. M., and Imbert, E. (2018). Social life cycle approach as a tool for promoting the market uptake of bio-based products from a consumer perspective. Sustain. 10: 1031.

Falcone, P. M., García, S. G., Imbert, E., Lijó, L., Moreira, M. T., Tani, A., Tartiu, V. E., Morone, P. (2019). Transitioning towards the bio-economy: Assessing the social dimension through a stakeholder lens. *Corporate Social Responsibility and Environmental Management*, 1-19, doi: 10.1002/csr.1791.

Fedderke, J., and Schirmer, S. (2006). The R&D Performance of the South African Manufacturing Sector, 1970-1993. *Economic Change*, 39, 125–151. DOI: 10.1007/s10644-007-9023-3.

Federal Ministry of Education and Research (BMBF) and Federal Ministry of Food and Agriculture (BMEL). (2015). Bioeconomy in Germany. Opportunities for a bio-based and sustainable future. Bonn and Berlin: Federal Ministry of Education and Research and Federal Ministry of Food and Agriculture. Accessed 20 June 2019, http://www.bmbf.de/upload_filestore/pub/Biooekonomie_in_Deutschland_Eng.pdf.

Federal Ministry of Food and Agriculture (BMEL). (2015). Fortschrittsbericht zur Nationalen Politikstrategie Bioökonomie.

https://www.bmel.de/SharedDocs/Downloads/Broschueren/fortschrittsbericht-biooekonomie.pdf? (accessed 13 March 2019).

Food and Agriculture Organization (FAO). (2016). How sustainability is addressed in official bioeconomy strategies at international, national and regional levels: An overview. Rome. Food and Agriculture Organization of the United Nations. Accessed 25 May 2019, http://www.fao.org/3/a-i5998e.pdf

Food and Agriculture Organization (FAO). (2018). Assessing the contribution of bioeconomy to countries' economy: A brief review of national frameworks. http://www.fao.org/3/I9580EN/i9580en.pdf (accessed 6 May 2019).

Frame, J. (1991). Modelling national technological capacity with patent indicators. *Scientometrics*, 22(3), 327-339.

Fritsche, U. R., and Iriarte L. (2014). Sustainability criteria and indicators for the bio-based economy in Europe: state of discussion and way forward. *Energies*, 7, 6825-6836.

Fukuzawa, N., and Ida, T. (2016). Science linkages between scientific articles and patents for leading scientists in the life and medical sciences field: The case of Japan. *Scientometrics*, 106(2), 629–644.

Fund, C., El-Chichakli, B., Patermann, C., Dieckhoff, P. (2015). Bioeconomy Policy (Part II) synopsis of national strategies around the world. A report from the German Bioeconomy Council 2015. http://gbs2015.com/fileadmin/gbs2015/downloads/bioeconomy-policy_part-II.pdf (Accessed 10 May 2019).

Funk, R. J., and Owen-Smith, J. (2016). A dynamic network measure of technological change. *Management Science*, 63(3), doi:10.1287/mnsc.2015.2366.

Fuss, J., Spassov, N., Begun, D. R., and Böhme, M. (2017). Potential hominin affinities of Graecopithecus from the Late Miocene of Europe. *PLoS ONE*, https://doi.org/10.1371/journal.pone.0177127.

Gambardella, A., Harhoff, D., and Verspagen, B. (2008). The value of European patents. *European Management Review*, 5(2), 69-84.

Garfield, E. (1964). Science Citation Index: A new dimension in indexing. *Science*, 144(3619), 649–654.

Garfield, E. (1966). Patent citation indexing and the notions of novelty, similarity, and relevance. *Journal of Chemical Documentation*, 6(2), 63-65.

Gittelman, M., and Kogut, B. (2003). Does good science lead to valuable knowledge? Biotechnology firms and the evolutionary logic of citation patterns. *Management Science*, 49(4), 366-382.

Global Bioeconomy Summit (GBS). (2018). Innovation in the global bioeconomy for sustainable and inclusive transformation and wellbeing. Accessed 12 January 2020, http://gbs2018.com/fileadmin/gbs2018/downloads/GBS_2018_Communique.pdf.

Godin, B. (2006). The Linear Model of Innovation: The Historical Construction of an Analytical Framework. *Science, Technology, and Human Values*, 31 (6): 639–667. doi:10.1177/0162243906291865

Gravett, N., Bhagwandin, A., Sutcliffe, R., Landen, K., Chase, M. J., Lyamin, O. I., Siegel, J.M., and Manger, P.R. (2017). Inactivity/sleep in two wild free-roaming African elephant matriarchs – Does large body size make elephants the shortest mammalian sleepers? *PLoS ONE*, https://doi.org/10.1371/journal.pone.0171903.

Griliches, Z. (1979). Issues in assessing the contribution of research and development to productivity growth. *The Bell Journal of Economics*, 92-116.

Griliches, Z. (1984). R&D, patents, and productivity. Chicago: University of Chicago Press.

Griliches, Z. (1990). Patent Statistics as economic indicators. *Journal of Economic Literature*, 28: 1661-1707.

Grupp, H., and Schmod, U. (1998). Patent statistics in the age of globalisation: new legal procedures, new analytical methods, new economic interpretation. *Research Policy*, 28, 377-396.

Guo, Y., Hu, Y., Zheng, M., and Wang, Y. (2013) Patent indicators: a window to pharmaceutical market success. Expert Opinion on Therapeutic Patents, 23:7, 765-771, DOI: 10.1517/13543776.2013.792806.

Haarich, S. (2017). Bioeconomy Development in EU Regions. Luxembourg.

Hall, B. H., Jaffe, A. B., and Trajtenberg, M. (2005). Market value and patent citations. *RAND Journal of Economics*, 36(1), 16-38.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D., and de Kroon, H. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE*, https://doi.org/10.1371/journal.pone.0185809.

Hansen, A., Budde, J., Karatay, Y. N., and Prochnow, A. (2016). CUDe-Carbon Utilization Degree as an Indicator for Sustainable Biomass Use. *Sustainability*, 8, 1028, doi:10.3390/su8101028.

Harhoff, D., and Reitzig, M. (2004). Determinants of opposition against EPO patent grants - The case of biotechnology and pharmaceuticals. *International Journal of Industrial Organization*, 22(4), 443–480.

Harhoff, D., Narin, F., Scherer, F., and Vopel, K. (1999). Citation frequency and value of patented inventions. *The Review of Economics and Statistics*, 81(3), 511-515.

Harhoff, D., Scherer, F. M., and Vopel, K. (2002). Citations, family size, opposition and the value of patent rights. *Research Policy*, 32(8), 1343-1363.

Hart, S., Hultink, E., Tzokas, N., Commandeur, H.R. (2003). Industrial companies' evaluation criteria in new product development gates. *Journal of Product Innovation Management*, 20, 22–36.

Henry, G., Trigo, E. J., 2010. The Knowledge Based Bio-Economy (KBBE) at work: from large scale experiences to instruments for rural and local development. ISDA,1-14.

Hinze, S., and Grupp, H. (1996). Mapping of R&D structures in transdisciplinary areas: new biotechnology in food sciences. *Scientometrics*, 37, 313-335.

International Monetary Fund (2021). World Economic Outlook Database, October 2021. www.imf.org. Accessed 25 October 2021.

Jaffe, A. B., Trajtenberg, M., and Henderson, R. (1993). Geographic localization of knowledge spillovers as evidenced by patent citations. *The Quarterly Journal of Economics*, 108(3), 577.

Jaffe, A., and de Rassenfosse, G. (2017). Patent citation data in social science research: overview and best practices. *Journal of the Association for Information Science and Technology*, 68(6), 1360-1374.

Jaffe, A., and Trajtenberg, M. (2002). Patents, citations and innovations. Boston, MA: MIT Press.

Jaffe, A., Trajtenberg, M., and Fogarty, M. S. (2000). The meaning of patent citations: Report on the NBER/ case-western reserve survey of patentees. NBER Working Paper No. W7631.

Jaffe, A.B., Trajtenberg, M., Henderson, R. (1993). Geographic localization of knowledge spill overs as evidence by patent citations. *Quarterly Journal of Economics*, 108, 577-598.

Jander, W., Grundmann, P. (2019). Monitoring the transition towards a bioeconomy: A general framework and a specific indicator. *Journal of Cleaner Production*, 236, 117564.

Kahn, M. (2011). A bibliometric analysis of South Africa's scientific outputs - some trends and implications. *South African Journal of Science*, 107(1), 1–6.

Karvonen, J., Halder, P., Kangas, J., and Leskinen, P. (2017). Indicators and tools for assessing sustainability impacts of the forest bioeconomy. *Forest Ecosystems*, 4, 2.

Kline, S.J. and Rosenberg, N. (1986). An overview of innovation. *In*: R. Landau and N. Rosenberg (eds.), The Positive Sum Strategy: Harnessing Technology for Economic Growth. National Academy Press. Washington. 275- 305

Ko, Y. (1992). An Economic Analysis of Biotechnology Patent Protection. Yale Law Journal 102 (3), 777-804. Accessed 29 September 2020, https://digitalcommons.law.yale.edu/ylj/vol102/iss3/4.

Kochhar, V.B and Verma, R.K. (1987). Indian Biotechnology Literature: A bibliometric study. *Annals of Library Science and Documentation*, 34(2), 61-70.

Kuznecova, I., Babica, V., Melecis, V., Baranenko, D., Ozarskis, M., and Gusca, J. (2018). Initial indicator analysis of bioethylen production pathways: International

Scientific Conference "Environmental and Climate Technologies", CONECT 2018. *Energy Procedia*, 147, 544-548.

Laibach, N., Börner, J., and Bröring, S. (2019). Exploring the future of the bioeconomy: An expert-based scoping study examining key enabling technology fields with potential to foster the transition toward a bio-based economy. *Technology in Society*, 58, 101118, https://doi.org/10.1016/j.techsoc.2019.03.001.

Lainez, M., González, J.M., Aguilar, A., and Vela, C. (2018). Spanish strategy on bioeconomy: Towards a knowledge based sustainable innovation. *New Biotechnology* 40 (2018) 87–95 http://dx.doi.org/10.1016/j.nbt.2017.05.006.

Lance, R. M., Stalcup, L., Wojtylak, B., and Bass, C. R. (2017). Air blast injuries killed the crew of the submarine H.L. Hunley. *PLoS ONE*, https://doi.org/10.1371/journal.pone.0182244.

Lewison, G. (1994). Publications from the European community's biotechnology action programme (BAP): multinationality, acknowledgment of support, and citations. *Scientometrics*, 31, 125-142.

Leydesdorff, L., and Bornmann, L. (2012). Mapping (USPTO) patent data using overlays to Google Maps. *Association for Information Science and Technology*, 63(7), 1442-1458.

Leydesdorff, L., and Heimeriks, G. (2001). The self-organisation of the European information society: The case of "biotechnology". *Journal of the American Society for Information Science and Technology*, 52(14), 1262-1274.

Leydesdorff, L.; Rotolo, D.; Rafols García, I. (2012). Bibliometric perspectives on medical innovation using the medical subject Headings of Pubmed. *Journal of the American Society for Information Science and Technology*, 63(11):2239-2253. doi:10.1002/asi.22715.

Li, B-W., Chen, C-J., and Wu, H.L. (2007). Predicting citations to biotechnology patents based on the information from the patent documents. *International Journal of Technology Management*, 40, 1-3. DOI: 10.1504/IJTM.2007.013528.

Lier, M., Aarne, M., Kärkkäinen, L., Korhonen, K.T., Yli-Viikari, A., and Packalen, T. (2018). Synthesis on bioeconomy monitoring systems in the EU Member States - indicator for monitoring the progress of bioeconomy. *Natural resources and bioeconomy studies*, 38/2018. http://jukuri.luke.fi/handle/10024/542249 (accessed 31 August 2019).

Lier, M., Kärkkäinen, L., Korhonen, K.T., and Packalen, T. (2019). Understanding the regional bioeconomy settings and competencies in 29 EU regions in 11 EU countries. Natural re-sources and bioeconomy studies 88/2019. 28 p. Natural Resources Institute. Finland, Helsinki 2019. Accessed 28 January 2020, https://www.researchgate.net/publication/339325269.

Lindqvist, A.N., Broberg, S., Tufvesson, L., Khalil, S., and Thomas Prade, T. (2019). Bio-Based Production Systems: Why Environmental Assessment Needs to Include Supporting Systems. *Sustainability*, 11, 4678; doi:10.3390/su11174678.

Litchtenberg, F., and Virabhak, S. (2002). Using patents data to map technical change in health-related areas. OECD Science, Technology and Industry Working Papers 2002/16, OECD Publishing, Paris. DOI: https://dx.doi.org/10.1787/522485718871.

Loizou, E., Jurga, P., Rozakis, S., Faber, A. (2019). Assessing the potentials of bioeconomy sectors in Poland employing input-output modelling, *Sustainability*, 11 (3), 594, https://doi.org/10.3390/su11030594.

Lokko, Y., Heijde, M., Schebesta, K., Scholtès, P., and Van Montagu, M. (2018). Biotechnology and the bioeconomy – towards an inclusive and sustainable industrial development. *New Biotechnology*, 40, 5-10.

López-Illescas, C., de Moya Anegón, F., and Moed, H.F. (2009). Comparing bibliometric country-by-country rankings derived from the Web of Science and Scopus: the effect of poorly cited journals in oncology. *Journal of Information Science*, 35(2), 244-256.

Mack, E. A., and Wrase, S. (2017). A Burgeoning Crisis? A Nationwide Assessment of the Geography of Water Affordability in the United States. *PLoS ONE*, https://doi.org/10.1371/journal.pone.0169488.

Magerman, T., Van Looy, B., and Debackere, K. (2011). In search of anticommons: Patent-paper pairs in biotechnology. An analysis of citation flows. MSI FEB Working paper, KU Leuven.

Magerman, T., van Looy, B., and Debackere, K. (2015). Does involvement in patenting jeopardize one's academic footprint? An analysis of patent-paper pairs in biotechnology. *Research Policy*, 44(9), 1702–1713.

Majore, G., Zakis, V., Zake, M., Ginters, E., Zakis, K., and Fjodorovs, A. (2015). Holistic Benchmarking of the Bio-economy in Protected Landscape Areas. *Procedia Computer Science*, 43, 118 – 126. doi: 10.1016/j.procs.2014.12.016.

Makhoba, X., and Pouris, A. (2016). Scientometric assessment of selected R&D priority areas in South Africa: A comparison with other BRICS countries. *African Journal of Science, Technology, Innovation and Development*, 8(2), 187-196.

Makhoba, X., and Pouris, A. (2017). Bibliometric analysis of the development of nanoscience research in South Africa. *South African Journal of Science*, 113, 1-9.

Makhoba, X., and Pouris, A. (2019a). A patentometric assessment of selected R&D priority areas in South Africa, a comparison with other BRICS countries. *World Patent Information*, 56, 20-28.

Makhoba, X., and Pouris, A. (2019b). A. Analysis of R&D efficiency in South Africa: a comparison with other BRICS countries. 2019 Proceedings of PICMET '19: Technology Management in the World of Intelligent Systems, https://ieeexplore.ieee.org

Mallick, A., Chandra Santra S., and Samal, A.C. (2015). An overview on Indian patents on biotechnology. *Recent Patents on Biotechnology*, 9(3), 198-213. DOI: 10.2174/1872208310666160325113553.

Mani, S. (2001). Government, Innovation and Technology Policy: An Analysis of the South African Experience since 1994. Paper presented at the International Forum on New Industrial Realities and Firm Behaviour in Africa, UNIDO and the Centre for the Study of African Economies, University of Oxford, September 20-22 2001. Accessed 16 March 2021, https://www.researchgate.net/publication/4777154_Government_and_Innovation_Policy_An_Analysis_of_the_South_African_Experience_since_1994.

Martens, B., and Saretzki, T. (1994). Quantitative-Analysis of thematic structures in the field of biotechnology - A study on the basis of conference data. *Scientometrics*, 30, 117-128.

Martin, M., Røyne, F., Ekvall, T., and Moberg, Å. (2018). Life cycle sustainability evaluations of bio-based value chains: reviewing indicators from a Swedish perspective. *Sustainability*, 10; 547.

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., and López-Cózar1, E.D (2018). Google Scholar, Web of Science, and Scopus: a systematic comparison of citations in 252 subject categories. *Journal of Informetrics*, 12(4), 1160-1177.

Matthews, A.P. (2012). South African Universities in world rankings. *Scientometrics*, 92(3), 675-695.

McCain, K.W. (1995a). The structure of biotechnology R&D. *Scientometrics*, 30, 117-128.

McCain, K.W. (1995b). Biotechnology in context: A database-filtering approach to identifying core and productive non-core journals supporting multidisciplinary R&D. *Journal of the America Society for Information Science*, 46, 306-317.

McCormick, K., Kautto, N., 2013. The Bioeconomy in Europe: An overview. Sustain. 5, 2589-2608.

McMillan, G.S., Narin, F., and Deeds, D. L. (2000). An analysis of the critical role of public science in innovation: the case of biotechnology. *Research Policy*, 29, 1-8.

Meho, L.I and Yang, K. (2006). Impact of data sources on citation counts and rankings of LIS Faculty: Web of Science vs Scopus and Google Scholar. *Journal of the American Society for Information Science and Technology*, 58(13), 2105-2125.

Mikhaylova, A.A. (2014). Evolution of the Innovation Process Models. *International Journal of Econometrics and Financial Management*, 2(4): 119-123. doi: 10.12691/ijefm-2-4-1.

Ministry of Science, Technology and Innovation (MOSTI) and Bioeconomy Corporation. (2016). Bioeconomy Transformation Program. Enriching the Nation, Securing the Future. http://www.bioeconomycorporation.my/wp-content/uploads/2011/11/publications/BTP_AnnualReport2016.pdf (accessed 13 March 2019).

Moen, O. (1999). The relationship between firm size, competitive advantages and export performance revisited. *International Small Business Journal*, 18(1), 53–72.

Molotja N., Parker S., and Mudavanhu P. (2019). Patterns of Investing into Business R&D in South Africa. *Foresight and STI Governance*, 13(3), 51–60. DOI: 10.17323/2500-2597.2019.3.51.60.

Mouysseta, L., Rais Assaa, C., Ay, J-S., Jiguetd, F., Lorrilière, R., and Doyena., L. (2019). Bioeconomic impacts of agroforestry policies in France. *Land Use Policy*, 85, 239-248. https://doi.org/10.1016/j.landusepol.2019.02.026.

Muizniece, I., Zihare, L., and Blumberga, D. (2019b). Obtaining the Factors Affecting Bioeconomy. *Environmental and Climate Technologies*, 23(1), 277-291, doi: 10.2478/rtuect-2019-0084 https://content.sciendo.com.

Muizniece, I., Zihare, L., Pubule, J., and Blumberga, D. (2019a). Circular Economy and Bioeconomy Interaction Development as Future for Rural Regions. Case Study of Aizkraukle Region in Latvia. *Environmental and Climate Technologies*, 23(3), 129-146, doi: 10.2478/rtuect-2019-0084 https://content.sciendo.com.

Mustapha, N., Blankley, W., Makelane, H., and Molotja, N. (2015). Trends in research and development expenditure in South Africa (2010–2013): Policy implications. HSRC Policy Brief 10 - Trends in RD Expenditure. DOI: 10.13140/RG.2.1.2852.5609

Naravaez-Berthelemot, N., Russell, J. M., Arvanitis, R., Waast, R., and Gaillard, J. (2002). Science in Africa: an overview of mainstream scientific output. *Scientometrics*, 54(2), 229–241.

Narin, F., Noma, E., and Perry, R. (1987). Patents as indicators of corporate technological strength. *Research Policy*, 16(2), 143-155.

National Council on Innovation (NACI). (2017). 2016 South African Science, Technology and Indicators. Accessed 23 June 2019, http://www.naci.org.za/wp-content/uploads/2018/07/South_African_Science_Technology_And_Innovation_Indicators_Report_2017.pdf.

National Advisory Council on Innovation (NACI). (2018). 2017 South African science technology and innovation indicators. NACI, Pretoria. Accessed 23 June 2020, https://www.dst.gov.za/index.php/resource-center/strategies-and-reports/2552-south-african-science-technology-and-innovation-indicators-2017.

National Advisory Council on Innovation (NACI). (2019). 2019 South African science technology and innovation indicators. NACI, Pretoria. Accessed 30 November 2020, https://www.dst.gov.za/index.php/resource-center/strategies-and-reports/2874-south-african-science-technology-and-innovation-indicators-2019.

National Advisory Council on Innovation (NACI). (2020). 2020 South African science technology and innovation indicators. NACI, Pretoria. Accessed 30 November 2020, https://www.dst.gov.za/index.php/resource-center/strategies-and-reports/2874-south-african-science-technology-and-innovation-indicators-2020.

National Development Plan (NDP) (2012). Government of the Republic of South Africa. Pretoria. Accessed 12 March 2019, http://www.gov.za/issues/national-development-plan-2030

Nedelea, A. M., Mironiuc, M., Huian, M. C., Bîrsan, M., and Bedrule-Grigoruţă, M. V., (2018). Modelled interdependencies between intellectual capital, circular economy and economic growth in the context of bioeconomy. *Amfiteatru Economic,* 20(49), 616-630.

Nederhof, A.J. (1988). Changes in publication patterns of biotechnologists: An evaluation of the impact of government stimulation programs in six industrial nations. *Scientometrics*, 14, 475-485.

Nordstrom, L.O. (1987). Applied versus basic science in the literature of plant biology: a bibliometric perspective. *Scientometrics*, 12, 381-394.

O'Brien, M., Wechsler, D., Bringezu, S., and Schaldach, R. (2017). Towards a systemic monitoring of the European bioeconomy: Gaps, needs and the integration of sustainability indicators and targets for global land use. *Land Use Policy*, 66; 162-171.

Organisation for Economic Cooperation and Development (OECD). (2000). Towards Sustainable Development. Indicators to measure progress. *Organisation for Economic Cooperation and Development*. Paris. http://www.oecd.org/site/worldforum/33703694.pdf (accessed 11 May 2019).

Organisation for Economic Co-operation and Development (OECD). (2002). Frascati Manual 2002: Proposed Standard Practice for Surveys on Research and Experimental Development, The Measurement of Scientific and Technological Activities, OECD Publishing, Paris, https://doi.org/10.1787/9789264199040-en.

Organisation for Economic Cooperation and Development (OECD). (2003). OECD Environmental Indicators: Development, Measurement and Use. *Organisation for Economic Cooperation and Development*. Paris. http://www.oecd.org/environment/indicators-modelling-outlooks/24993546.pdf (Accessed 10 May 2019).

Organisation for Economic Co-operation and Development (OECD). (2005). A framework for Biotechnology Statistics. OECD Publishing. Paris. Accessed 10 October 2019, http://www.oecd.org/sti/inno/34935605.pdf

Organisation for Economic Co-operation and Development (OECD). (2008). Compendium of Patent Statistics. OECD Publishing. Paris. Accessed 12 August 2020. http://www.oecd.org/science/inno/37569377.pdf

Organisation for Economic Co-operation and Development (OECD). (2009a). The bioeconomy to 2030: Designing a policy agenda. Main findings and policy conclusions. *Organisation for Economic Cooperation and Development*. Paris.

Organisation for Economic Co-operation and Development (OECD). (2009b). OECD Patent Statistics Manual. OECD Publishing. Paris. Accessed 10 October 2019, https://doi.org/10.1787/9789264056442-7-en.

Organisation for Economic Co-operation and Development (OECD). (2009c). "Health-related patents", OECD Science, Technology and Industry Scoreboard 2009, OECD Publishing, Paris. DOI: https://doi.org/10.1787/sti_scoreboard-2009-22-en.

Organisation for Economic Co-operation and Development (OECD). (2009d). "Patents in environment-related technologies", in OECD Science, Technology and Industry Scoreboard 2009, OECD Publishing, Paris. DOI: https://doi.org/10.1787/sti_scoreboard-2009-18-en.

Organisation for Economic Co-operation and Development (OECD). (2009e). "Biotechnology patents", in OECD Science, Technology and Industry Scoreboard 2009. OECD Publishing, Paris. doi: https://doi.org/10.1787/sti_scoreboard-2009-25-en.

Organisation for Economic Co-operation and Development (OECD). (2015). Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development. Accessed 19 January 2021, http://dx.doi.org/10.1787/9789264239012-en

Organisation for Economic Cooperation and Development (OECD). (2016). Compendium of bibliometric science indicators, Organisation for Economic Cooperation and Development. Paris.

Organisation for Economic Co-operation and Development (OECD). (2017). "Business R&D", in OECD Science, Technology and Industry Scoreboard 2017: The digital transformation, OECD Publishing, Paris. DOI: https://doi.org/10.1787/sti_scoreboard-2017-21-en.

Organisation for Economic Co-operation and Development (OECD). (2018a). Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition, The Measurement of Scientific, Technological and Innovation Activities, OECD Publishing, Paris/Eurostat, Luxembourg. https://doi.org/10.1787/9789264304604-en

Organisation for Economic Co-operation and Development (OECD). (2018b). Report on statistics and indicators of biotechnology and nanotechnology. OECD Science, Technology and Industry Working Papers 2018/06. Accessed 10 October 2019, https://dx.doi.org/10.1787/3c70afa7-en.

Organisation for Economic Co-operation and Development (OECD). (2019a). *OECD.Stat. Science, Technology and Patents. Patents Statistics. Patents by technology*. Accessed 10 October 2019, https://stats.oecd.org.

Organisation for Economic Co-operation and Development (OECD). (2019b). *OECD.Stat. Trade in Value Added (TiVA): Principal indicators*. Accessed 14 January 2021, https://stats.oecd.org.

Organisation for Economic Co-operation and Development (OECD). (2020). Triadic patent families (indicator). Accessed 25 November 2020, doi: 10.1787/6a8d10f4-en.

Organisation for Economic Co-operation and Development (OECD). (2021). Gross domestic spending on R&D (indicator). doi: 10.1787/d8b068b4-en (Accessed on 16 March 2021).

Palangkaraya, A. (2012). The Link between Innovation and Export: Evidence from Australia's Small and Medium Enterprises. ERIA Discussion Paper Series. ERIA-DP-2012-08. Accessed 3 February 2021, https://www.eria.org/ERIA-DP-2012-08.pdf.

Parisi, C., and Ronzon, T. (2016). A Global View of Bio-Based Industries: Benchmarking and Monitoring Their Economic Importance and Future

Developments: EU-Brazil Sector Dialogues Workshop, 18–19 February 2016, JRC - Seville, https://doi.org/10.2788/153649. JRC Technical Reports.

Paruk, F., Blackburn, J.M., Friedman, I.B., and Mayosi, B.M. (2014). National expenditure on health research in South Africa: What is the benchmark? *South African Medical Journal*, 104 (7), 468-474. DOI:10.7196/SAMJ.6578

Paşnicu, D., Ghenţa, M., and Matei, A. (2019). Transition to bioeconomy: Perceptions and behaviours in central and eastern Europe. *Amfiteatru Economic,* 21(50), 9-23.

Patra, S.K., and Muchie, M. (2017). Role of Innovation System in Development of Biotechnology in South Africa. *Asian Biotechnology and Development Review*, 19(1), 3-30.

Pavitt, K. (1985). Patent statistics as indicators of innovative activities: Possibilities and problems. *Scientometrics*, 7(1-2), 77-99.

Pereira, T.T.S. (2000). A Bibliometric Study of the Portuguese Research System in Biotechnology. Instituto Nacional de Engenharia, Tecnologia e Inovação. DMS 020/2000. Accessed 22 July 2019, http://www.ces.uc.pt/myces/UserFiles/livros/192_clusterPT_bibliometrics.pdf

Petruzzelli, A, M., Rotolo, D., and Albino, V. (2014). Determinants of patent citations in biotechnology: an analysis of patent influence across the industrial and organizational boundaries. (April 1, 2014). SWPS 2014-05, *Technological Forecasting and Social Change*, Forthcoming, Accessed 23 November 2020, https://ssrn.com/abstract=2742112.

Pfau, S. F., Hagens, J. E., Dankbaar, B., and Smits, A. J. M. (2014). Visions of sustainability in bioeconomy research. *Sustainability*, 6, 1222-1249.

Philippidis, G., and Sanjuán-López, A.I. (2018). A Re-Examination of the Structural Diversity of Biobased Activities and Regions across the EU. *Sustainability*, 10, 4325; doi:10.3390/su10114325.

Pieratti E., Paletto A., De Meo I., Fagarazzi C., and Migliorini Giovannini M. R. (2019). Assessing the forest-wood chain at local level: A Multi-Criteria Decision Analysis (MCDA) based on the circular bieconomy principles. *Annals of Forest Research*, 62(1). DOI: 10.15287/afr.2018.1238.

Piotrowski, S., Carus, M., and Carrez, D. (2018). European Bioeconomy in Figures 2008 – 2015, nova Institute, pp. 1–17. https://biconsortium.eu/sites/biconsortium.eu/files/documents/Bioeconomy_data_2015_20150218.pdf

Pla-Barber, J., Alegre, J. (2007). Analysing the link between export intensity, innovation and firm size in a science-based industry. *International Business Review*,16, 275–293. doi:10.1016/j.ibusrev.2007.02.005

Plehn-Dujowich, J.M. (2009) Firm size and types of innovation. *Economics of Innovation and New Technology*, 18:3, 205-223, DOI: 10.1080/10438590701785850

Podolny, J.M., Stuart, T.E. and Hannan, M.T. (1996). Networks, knowledge and niches: Competition in the worldwide semiconductor industry, 1984-1991. *American Journal of Sociology*, 102(3), 659-689.

Pouris, A. (2003). South Africa's Research Publication Record: The Last Ten Years. *South African Journal of Science*, 99, 425–428.

Pouris, A. (2006). The international performance of South African academic institutions; a citation assessment. *Higher Education*, 54(4), 501–509.

Pouris, A. (2012) Scientometric research in South Africa and successful policy instruments. *Scientometrics*, 91:317–325.

Pouris, A., and Pouris, A. (2009a). Biotechnology Research in South Africa: A Benchmarking Exercise. *Journal of Business Chemistry*, 6(1), 31-41.

Pouris, A., and Pouris, A. (2009b). The state of science and technology in Africa (2000–2004): a scientometric assessment. *Scientometrics*, 79(2), 297–309.

Pouris, A., and Pouris, A. (2011). Patents and economic development in South Africa: Managing intellectual property rights. *South African Journal of Science*, 107(11/12), 1-10. http://dx.doi.org/10.4102/sajs.v107i11/12.355.

Quach, U., Thorsteinsdóttir, H., Renihan, J., Bhatt, A. (2006). Biotechnology patenting take off in developing countries. *International Journal of Biotechnology*, 8, 43-59.

Rafiaani, P., Kuppens, T., Van Dael, M., Azadi, H., Lebailly, P., and Van Passel, S. (2017). Social sustainability assessments in the biobased economy: Towards a systemic approach. *Renewable and Sustainable Energy Reviews*, 82, 1839-1853.

Ramani, S.V., and DeLooze, M.A. (2000). A note on using patent statistics to obtain competition indicators. *Scientomentrics*, 49, 511-515.

Rip, A., and Courtial, J. P. (1984). Co-word maps of biotechnology: an example of cognitive scientometrics. *Scientometric*s, 6, 381-400.

Rodríguez-Salvador, M., Rio-Belver, R.M., and Garechana-Anacabe, G. (2017). Scientometric and patentometric analyses to determine the knowledge landscape in innovative technologies: The case of 3D bioprinting. PLOS ONE, https://doi:10.1371/journal.pone.0180375.

Rogers, E. (2003). Diffusion of Innovations, 5th edition, Free Press. ISBN 0-7432-2209-1

Ronzon, T., and M’barek, R. (2018). Socioeconomic indicators to monitor the EU’s bioeconomy in transition. *Sustainability*, 10 (6), 1745, https://doi.org/10.3390/su10061745.

Ronzon, T., Piotrowski, S., M’barek, R., and Carus, M. (2017) A systematic approach to understanding and quantifying the EU’s bioeconomy. *Bio-based and Applied Economics*, 6(1),1-17, https://doi.org/10.13128/BAE-20567.

Scarlat, N., Dallemand, J-F., Monforti-Ferrario, F., and Nita, V. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environmental Development*, 15, 3 - 34. http://dx.doi.org/10.1016/j.envdev.2015.03.006.

Scherer, F. (1965). Firm size, market structure, opportunity and the output of patented inventions. *American Economic Review*, 55, 1097.

Schmookler, J. (1966). Invention and economic growth. Harvard U.P.

Sevukan, R., and Sharma, J. (2008). Bibliometric analysis of research output of biotechnology faculties in some Indian central universities. *DESIDOC Journal of Library and Information Technology*, 28(6), 11-20.

Sheldon, R. A. (2018). Metrics of Green Chemistry and Sustainability: Past, Present, and Future. *ACS Sustainable Chemistry and Engineering*, 6(1), 32-48. https://doi.org/10.1021/acssuschemeng.7b03505.

Sick, N., Preschitschek, N., Leker, J., and Bröring, S. (2019). A new framework to assess industry convergence in high technology environments. *Technovation*, 84-85, 48-58.

Siebert, A., Bezama, A., O’Keeffe, S., and Thrän, D. (2017). Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. *Journal of Cleaner Production*, 172, 4074-4084.

Singh, H., and Saxena, S. K. (1992). Application of biotechnology in mass health care – literature trend. *Annals of Library Science and Documentation*, 39(1), 19-25.

Spierling, S., Knüpffer, E., Behnsen, H., Mudersbach, M., Krieg, H., Springer, S., Albrecht, S., Herrmann, C., and Endres, H-J. (2018). Bio-based plastics - A review of environmental, social and economic impact assessments. *Journal of Cleaner Production*, 185,476-491. https://doi.org/10.1016/j.jclepro.2018.03.014.

Squicciarini, M., Dernis, H., and Criscuolo, C. (2013), Measuring Patent Quality: Indicators of Technological and Economic Value. OECD Science, Technology and Industry Working Papers, No. 2013/03. http://dx.doi.org/10.1787/5k4522wkw1r8-en.

Sridhar, K. R. (2005). Recent trends in biotechnology. *Current Science*, 88,7.

Staffas, L., Gustavsson, M., and McCormick, K. (2013). Strategies and Policies for the Bioeconomy and Bio-Based Economy: An Analysis of Official National Approaches. *Sustainability*, 5, 2751-2769.

Stegmann, P., Londo, M., and Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation and Recycling: X 6*, 100029. https://doi.org/10.1016/j.rcrx.2019.100029.

Talavyria, M. P., Lymar, V.V., and Baidala, V.V. (2017). Indicators for analysis of the bioeconomy in Ukraine. *EkoHomika ANK*, 3, 44-50.

The White House. (2012). National Bioeconomy Blueprint. Washington. Accessed 14 March 2019, http://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf.

Thomas, S.M. (1992). The evaluation of plant biomass research: a case study of the problems inherent in bibliometric indicators. *Scientometrics*, 23, 149-167.

Tijssen, R. J. (2001). Global and domestic utilization of industrial relevant science: Patent citation analysis of science-technology interactions and knowledge flows. *Research Policy*, 30(1), 35-54. https://doi.org/10.1016/S0048-7333(99)00080-3.

Trajtenberg, M. (1990a). Economic analysis of product innovation: The case of CT scanners (Vol. 160). Harvard University Press Cambridge: MA.

Trajtenberg, M. (1990b). A penny for your quotes: Patent citations and the value of innovations. *RAND Journal of Economics*, 21(1), 172-187.

United States Department of Agriculture (USDA). (2011). Biobased Economy Indicators; A report to the U.S. Congress. National Technical Information Service. Washington. Accessed 12 March 2019, www.usda.gov/oce/reports/energy/index.htm

Van Beuzekom, B, and Arundel, A. (2009). OECD Biotechnology Statistics. OECD Publications. Accessed 30 January 2021, https://www.researchgate.net/publication/239575102_OECD_Biotechnology_Statistics_2009.

Van Beveren, I, and Vandenbussche, H. (2010). Product and Process Innovation and Firms' Decision to Export, *Journal of Economic Policy Reform*, 13(1), 3- 24.

Van Raan, A.F.J. (2017). Patent Citations Analysis and its value in research evaluation: A review and a new approach to map technology-relevant research. *Journal of Data and Information Science*, 2(1), 23-50. DOI: 10.1515.jdis-2017-0002.

Van Schoubroeck, S., Van Dael, M., Van Passel, S., and Malina, R. (2018). A review of sustainability indicators for biobased chemicals. *Renewable and Sustainable Energy Reviews*, 94, 115-126.

Von Wartburg, I., Teichert, T., and Rost, K. (2005). Inventive progress measured by multi-stage patent citation analysis. *Research Policy*, 34(10), 1591-1607.

Wagner, A.B. (2015). A Practical Comparison of Scopus and Web of Science Core Collection. http://hdl.handle.net/10477/38568. Accessed 20 March 2019.

Wakelin, K. (1998). Innovation and Export Behaviour at the Firm Level, *Research Policy*, 26 (7-8), 829-41.

Walwyn, D., and Cloete, L. (2016). Universities are becoming major players in the national system of innovation. *South African Journal of Science*, 112(7/8), Article #2015-0358, 8 pages. http://dx.doi.org/10.17159/sajs.2016/20150358.

Wang, S. J. (2007). Factors to evaluate a patent in addition to citations. *Scientometrics*, 71(3), 509-522.

Webb, C., Dennis, H., Harhoff, D., and Hoisl, K. (2005). Analysing European and international patent citations: A set of EPO patent database building blocks. OECD STI Working Paper 2005/09. https://dx.doi.org/10.1787/883002633010.

Wen, X., Quacoe, D., Quacoe, D., Appiah, K., and Danso, B. A. (2019). Analysis on bioeconomy's contribution of GDP: Evidence from Japan. *Sustainability*, 11, 712.

Wesseler, J., and von Braun, J. (2017). Measuring the bioeconomy: economics and policies. *Annual Review of Resource Economics*, 9, 275–298. https://doi.org/10.1146/annurev-resource-100516-053701.

William, S. C., and Scherer, F.M. (1969). Patent Statistics as a Measure of Technical Change. *Journal of Political Economy*, 77 (3), 392-398. https://doi.org/10.1086/259522.

Wydra, S. (2020). Measuring innovation in the bioeconomy – Conceptual discussion and empirical experiences. *Technology in Society*, 61, 101242. https://doi.org/10.1016/j.techsoc.2020.101242.

Yao, Q., Chen, K., Yao, L., Lyu, P., Yang, T., Luo, F., Chen, S-Q., He, L-Y., and Liu, Z-Y. (2014). Scientometric trends and knowledge maps of global health systems research. *Health Research Policy and Systems*, https://doi:10.1186/1478-4505-12-26.

Zeug, W., Bezama, A., Moesenfechtel, U., Jähkel, A., and Tharän, D. (2019). Stakeholders' interests and perceptions of bioeconomy monitoring using a sustainable development goal framework. *Sustainability*,11, 1511.

Zheng, J., Zhao, Z., Zhang, X., Huang, M., and Chen, D. (2014). Influences of counting methods on country rankings: a perspective from patent analysis, *Scientometrics*, 98 (3), 2087–2102, https://doi.org/10.1007/s11192-013-1139-9.

Zucker, L.G., Darby, M. R., and Brewer, M. B. (1994). Intellectual Capital and the Birth of U.S Biotechnology Enterprises. National Bureau of Economic Research 4653. Accessed 2 July 2019, http://www.nber.org/papers/w4653.pdf.

APPENDICES

A.1 Ethics approval

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie / Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

Reference number: EBIT/124/2019

Mr TL Bambo
Department: Engineering and Technology Mgt
University of Pretoria
Pretoria
0083

Dear Mr TL Bambo

FACULTY COMMITTEE FOR RESEARCH ETHICS AND INTEGRITY

Your recent application to the EBIT Research Ethics Committee refers.

Conditional approval is granted.

This means that the research project entitled "Governance and Development of Indicators for the Bioeconomy in South Africa" is approved under the strict conditions indicated below. If these conditions are not met, approval is withdrawn automatically.

Conditions for approval
1. From the application form the researcher seems to have no intention to question people as informants (interview/survey) however the researcher has ticked "yes" under section 3.3 in the application form. The recommended conditional approval is based on no interview/survey is to be conducted by the researcher.

This approval does not imply that the researcher, student or lecturer is relieved of any accountability in terms of the Code of Ethics for Scholarly Activities of the University of Pretoria, or the Policy and Procedures for Responsible Research of the University of Pretoria. These documents are available on the website of the EBIT Ethics Committee.

If action is taken beyond the approved application, approval is withdrawn automatically.

According to the regulations, any relevant problem arising from the study or research methodology as well as any amendments or changes, must be brought to the attention of the EBIT Research Ethics Office.

The Committee must be notified on completion of the project.

The Committee wishes you every success with the research project.

Prof JJ Hanekom
Chair: Faculty Committee for Research Ethics and Integrity
FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

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& technology
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Ref 3/2/2 Enq: Ms Dina Gwamba Tel: (012) 843 6686 Fax: 086 550 8443

Mr T Bambo
Chief Directorate: Biotechnology

Dear Mr Thabang Bambo

<u>ETHICAL CLEARANCE TO CONDUCT A RESEARCH STUDY</u>

Your request to conduct a research study on "Governance and Development of indicators for the Bio-economy in South Africa" is hereby acknowledged.

Kindly note that your request to conduct a research study is approved. The approval is granted subject to your compliance with the Protection of Information Act, 1982 (Act No. 84 of 1982) section 4. "Prohibition of disclosure of certain information"

Yours sincerely,

MR M MOTSWIANE
DIRECTOR: TM, OD & PM
DATE: 21/05/19