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Scientometric assessment of R&D priority areas in South Africa: a comparison with other BRICS countries

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SUMMARY

SCIENTOMETRIC ASSESSMENT OF R&D PRIORITY AREAS IN SOUTH AFRICA: A COMPARISON WITH OTHER BRICS COUNTRIES

by

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Keywords: Scientometrics, patentometrics, bibliometrics, R&D priority areas, South Africa, BRICS R&D efficiency

The study aimed to look at the priority areas of South African terms of technology development and the impact thereof. In terms of publications, a bibliometric analysis of selected research priority areas in South Africa was done using the Web of Science database for the period 2001 - 2015. The performance of the country in the areas of biotechnology, energy, astronomy and palaeontology in terms of the publication output in these areas is compared using two classic scientometric indicators, the activity and attractivity indices. These are important priority areas as highlighted in various government policy documents and the aim was to identify if outputs in these fields are corresponding with government policy. The study also identifies leading institutions in the country in terms of publication output, while the performance is also benchmarked against that of the other BRIC (Brazil, Russia, India and China) group of countries, as well as Egypt. It is found that South Africa has a relatively high output in research areas in which it enjoys geographical advantage, such as astronomy and palaeontology, and compares favourably with comparator countries in all

areas reviewed. In terms of the institutional profile, and based on publication outputs over the period considered, the University of Cape Town is a leader in energy, the University of Stellenbosch in biotechnology, the University of the Witwatersrand in palaeontology, and the National Research Foundation in the area of astronomy.

The study then evaluated the priority areas in terms of patents. It was found that South Africa is the most prolific producer of patents in the African continent. This study assessed the inventive activity through patents registered by South African researchers worldwide, using the WIPO database. The focus of the study was on research priority areas documented in the South African government policy documents. The research priority areas considered were ICT, nanotechnology, biotechnology, climate change, energy and health. Patents in the areas were compared with the BRICS (Brazil, Russia, India, China and South Africa) countries and Egypt. The comparison was done using the revealed technological advantage, sometimes referred to as the specialisation index. It was found that two African countries have not increased their patent share significantly and are yet to find their specialisation. It was found that while South Africa is doing well in terms of patenting in general, with patents showing an upward trend, the profile of inventions being patented are not necessarily aligned with the priority areas as documented in government policy.

Another question that remained was how South Africa is progressing in developing emerging technologies, with nanotechnology and nanoscience as a case study. This is one of the country's priorities and a fast-growing scientific research area internationally, and is classified as an important emerging research area. In response to this, South African researchers and institutions have also increased their efforts in this area. A bibliometric study of articles, as indexed in the Web of Science, considered the development in this field, including the growth in literature, collaboration profile and the research areas that are more within the country's context. It also looked at public institutions that are more active in this arena, including government policy considerations as guided by the Nanoscience and Nanotechnology Strategy launched in 2005. The study found that the number of nanotechnology publications have shown remarkable growth ever since. The articles are spread through many journals with *Electrochimica acta* having the most articles, followed by *Journal of Nanoscience and Nanotechnology*. These publications fall within the traditional domains of chemistry and physics. In terms of the institutional profile and based on publication outputs over the period reviewed, the Council for Scientific and Industrial Research is a leading producer of publications in nanotechnology, followed by the University of Witwatersrand - both institutions are based in Gauteng Province. There is a high level of international collaboration with different countries within this field, the most productive of which is with India, then USA, and thirdly, China, as measured through co-authorship.

Finally, R&D efficiency, as expressed by the publication and patent outputs in scientific fields compared with the overall investment in R&D, was studied. The study focussed on the two important fields in South Africa; nanotechnology and biotechnology. In addition to this, South Africa's R&D efficiency in all scientific fields was compared to that of the other BRICS countries. Data on R&D expenditure was used as input in the R&D process to achieve this comparison. The study found that, within South Africa, nanotechnology has been doing well on both patent and publications produced per US dollar spent on research development. The efficiency in terms of publications in this field started to fall slightly in 2013, to be equivalent to that of biotechnology. In context of the BRICS countries, it was found that South Africa has the highest R&D efficiency as measured by both patents and publications. This may offer some lessons to its bigger BRICS partners in terms of best practice in keeping the cost low and productivity high despite a relatively small science system.

Relevant literature reviewed in this research includes the use of bibliometrics methods for science and technology studies. The priority areas and the country-specific issues are also discussed, with particular emphasis to challenges in developing countries. While the study focussed on developing countries, the BRICS grouping, mainstream literature provided a useful background, especially with respect to designing the methodologies for the data collection. The conceptual models discussed in this study – the TENs and the Triple helix – all emphasise the multi-agency approach to innovation, with the government being just one of the actors in the innovation ecosystem. The low level of industrial involvement in

development of the priority areas, as indicated in patenting and publication trends, indicates that this one important player is missing in the system that should include all the players, which are the academia, industry and government. Strategies should be put in place to incentivise private sector R&D investment to raise the GERD that is currently very low when compared to other countries.

Keywords

Scientometrics, patentometrics, bibliometrics, R&D priority areas, South Africa, BRICS R&D efficiency

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LIST OF ABBREVIATIONS

AAGR	Average annual growth rate
AAI	Attractivity index
AJSTID	African Journal of Science, Technology, Innovation & Development
AAI	Attractivity index
AI	Activity index
ASEAN	Association of South East Asian
BERD	Business Expenditure on Research and Development
BRICS	Brazil, Russia, India, China (& South Africa)
CIVETS	Colombia, Indonesia, Vietnam, Egypt, Turkey and South Africa
DST	Department of Science and Technology
CIPC	Companies and Intellectual Property Commission
CSIR	the Council for Scientific and Industrial Research
DWPI	Derwent World Patents Index
EPO	European Patent Office
FDI	Foreign Direct Investment
GERD	Government Expenditure of Research and Development
GDP	Gross Domestic Product
HSRC	Human Sciences Research Council
ICT	Information and Communications Technology
IPC	International Patent Classification
INPI	National Institute of Industrial Property (Brazil)
JPO	Japan Patent Office
NACI	National Advisory Council on Innovation
N&N	Nanoscience and Nanotechnology
NNI	National Nanotechnology Initiative (USA)
NIPMO	National Intellectual Property Management Office
NRF	National Research Foundation

OECD	Organisation for Economic Co-operation and Development
PCT	Patent Cooperation Treaty
RTA	Relative Technological Advantage
R&D	Research and Development
SCI	Science Citation Index
SAJS	South African Journal of Science
SALT	Southern African Large Telescope
SIPO	State Intellectual Property Office
SKA	Square Kilometre Array
SAAO	South African Astronomical Observatory
SADC	Southern African Development Community
SANI	South African Nanotechnology Initiative
SUN	Stellenbosch University
TIA	Technology Innovation Agency
USPTO	United States Patents and Trademarks Office
USPC	United States Patent Classification
UCT	University of Cape Town
WIPO	World Intellectual Property Office
WPI	World Patent Information
WOS	Web of Science

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

Innovation is now globally accepted to be a major factor behind economic development and competitiveness for individual firms, regions and nations (Tödtling and Trippl, 2005). Science and technology, or at least scientific knowledge, as measured by the number of publications, is increasingly accepted as a key factor of economic growth (Mansfield, 1991; Narin, Hamilton & Olivastro, 1997). Additionally, it was established as early as 1979 that there is a direct correlation between the economic indicators such as GDP and GDP per capita, and the scientometric indicators such as number of research articles and citations (de Price, 1979). This is hardly a surprise since research contributes directly to the knowledge-based economy, therefore, those countries with higher level of research might have a higher rate of knowledge-based economy as part of the GDP. Hence the effort expended in trying to understand the scientometric indicators and how these can be advanced in order to affect the knowledge-based part of the GDP.

Most countries, therefore, consider technology development in their policies to build their economic strength to improve the lives of their citizens. The policy makers in South Africa recognised this and so the country adopted the National Research and Development Strategy in 2002 to enable the transition from a resource-based economy to a knowledge economy (DST, 2002). In order to drive the creation of this knowledge-driven economy, a number of targeted interventions and investments in specific fields of science were made. The strategy outlines specific areas of technology that have been identified for development for strategic reasons. Unfortunately, little is known about the impact of these policies as many countries, in particular developing countries, struggle with capacity to measure the relative progress in technology development. This measurement of a system is very crucial due to the need to identify whether the interventions are delivering the intended outcomes. The study considers certain institutional arrangements in the R&D value chain, with specific emphasis on those related to the commercialisation of R&D output specifically patenting industry-university collaboration and incubation activity. Therefore, the study will attempt to unpack some of the challenges as well as giving policy direction. It will seek to add to the existing body of knowledge on the contribution of R&D to economic development and the determinants of a successful R&D-led economic development in South Africa.

One of the interventions was the introduction of the Biotechnology Strategy (DST, 2001), after which the government, through the DST, allocated R450 million between 2004 and 2007 for this initiative most of which was used to establish the biotechnology regional innovation centres (Al-bader, Frew, Essajee, Liu, Saar & Singer, 2009). The main goal of the centres was to develop commercial products in biotechnology with two of these centres located in the KwaZulu-Natal Province, one in the Western Cape and one in Gauteng Province. Therefore, there is a need to understand how these are performing relative to their purpose and relative to international outputs. The purpose of this paper is to identify key trends in specific priority technical fields in South Africa and to provide a foundation for policy planning. The selected areas are evaluated and compared for research performance in an effort to provide an integrated perspective using a bibliometrics approach.

This thesis aims to study, evaluate and compare research performance of South Africa in priority areas such as health, nanotechnology, palaeontology, biotechnology, astronomy and energy-based upon the Science Citation Index (SCI). This is done using the publications as indexed in the Science Citation Index (SCI) databases as provided by Thomson Reuters. The Web of Science by Clarivate Analytics and the Scopus established in 2004 by Elsevier are the two most widely used databases. While the Web of Science is the older - more than 50 years -

and well stablished of the two previous studies have shown that the results from both databases do not differ significantly for country level comparisons (Archambault, Campbell, Gingras, & Larivière, 2009). The aim is to establish developments in the identified fields as to whether South African research output is aligned with the S&T strategic objectives of the country, to establish the current status of these areas and to establish the progress made so far, including the relative progress of each area in South Africa.

1.1.2 Research gap

This research aims to close the gap in terms of the link between the policy objectives and outcomes. Current statistics produced in the typical R&D survey tend to give an overall picture of the performance of the science system in terms of number of patents, publications, and R&D expenditures of the overall system. This data does not measure output per R&D priority area as outlined in the government policy documents. This thesis addresses this gap using the patent and publications data for each of the selected priority areas.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The research will answer the following three related questions with sub-questions:

1. **What are the publication trends in the selected areas of South Africa's strategic R&D priority research areas**. The research must provide some answers to the following two research sub-questions:

1.1 What is the status of South African research outputs of the selected science and technology priority area? What is the level of output in these fields, and what is their stage of development? To answer this, the research considered the publication profile, citation profile as well as institutional profile for each of the fields.

1.2 What is South African performance relative to other countries? The performance of South Africa is compared with other BRICS countries and includes a comparison with one African country; the country selected was Egypt as it is the second most productive country in Africa in terms of publications.

2. **What are the patenting trends in the selected areas of South Africa's strategic R&D priority research areas.** The research must provide some answers to the following two research sub-questions:
2.1 What is the status of South Africa in technological development in each of the selected priority areas? In this case, the study considers inventive activity through patent profile for each of the research areas.
2.2 What is the performance of South Africa in comparison to other BRICS countries (Brazil, Russia, India & China), and compared to Egypt?

3. **How is South Africa doing in terms of developing new and emerging technologies**? Emerging technologies tend to be interdisciplinary and promise a bigger impact than conventional technology. This study looks at the development of nanoscience and nanotechnology specifically the publications output since the introduction of the Nanoscience and Nanotechnology Strategy in 2005.

The performance of South Africa is studied with attention to publication and patenting trends, citation profile, collaboration profile with other countries and institutional profile. The study includes a comparison with at least one other African country, which is Egypt. This is done with due consideration that the priorities of the South African government may not exactly be the same as the priorities of the other comparator countries, in particular. Different countries, even those with same priorities, may assign different importance on each indicator or priority, based on their individual circumstance. The study makes use of patent data from WIPOs PATENTSCOPE and publications data from Thomson Reuters Web of Science.

4. **How efficient is South Africa in the utilisation of its R&D resources?**

In this part of the study, we look at how efficient the system is in converting the inputs, specifically R&D expenditure, to outputs, specifically publications and patents.

4.1 How efficient is the South African national system of research and development? In this part of the study, the performance is compared to that of the other BRICS countries.

4.2 How efficient are the resources used in the development of its top two priority areas in South Africa? In this case, the study considered R&D efficiency of biotechnology and nanotechnology.

1.3 APPROACH

In answering the research questions mentioned in section 1.2, the approach of the study will include:

- The collection of bibliometrics data for the selected priority areas, compare their performance with each other and compare with comparator countries, namely the BRICS countries and Egypt
- Collection of patent data in selected priority areas, compare their performance with each other and the comparator countries, namely BRICS and Egypt.
- Study one of the emerging technologies, namely nanoscience, and consider how it has progressed since the introduction of the N&N Strategy in 2005.
- Collection of expenditure data to establish the R&D efficiency profile of South Africa compared to its BRICS partners.

1.4 RESEARCH GOALS

In answering the research questions mentioned in section 1.2, the study aims to:

- Establish the publication profile in the selected priority areas, compare their performance with each other and compare with comparator countries, namely the BRICS countries and Egypt
- Establish the patenting trends in these priority areas, compare their performance with each other and the comparator countries, namely BRICS and Egypt.
- Study one of the emerging technologies, namely nanoscience, and consider how it has progressed since the introduction of the N&N Strategy in 2005.
- Establish the R&D efficiency profile of South Africa compared to its BRICS partners.

1.5 RESEARCH CONTRIBUTION

There is a deficiency of literature on innovation, and science and technology studies, particularly in developing countries. Research on evaluation of research in priority areas, South Africa, through a patentometrics and bibliometrics approach has not been found thus far. Much less likely using WIPO patent and WoS publication data during the period of 2001 - 2015. Further, most of the studies based on publications, patent statistics have largely focused on developed countries; less developed and developing countries have remained largely unrepresented. The study, for the first time, provides the quantitative study of performance of South Africa in terms of its R&D priority areas using patents from WIPO Patentscope as well as publication from the Clarivate Analytics (formerly Thomson Reuters) Web of Science databases. Recognising that different areas have different publishing and patenting profiles, this study proposes a set of relevant indicators that enable the comparison of different areas using index based on the Balassa Index (1965). In addition, while there is a lot of research about the

BRICS countries' economies, hardly any research exists that compares the countries in terms of scientific performance. Therefore, a comparative study on the subject should contribute significantly to the current body of knowledge in this field. This thesis has additional features in that it considers the development of a relatively new research area, nanoscience and nanotechnology; an area of fast growth internationally, and provides a South African perspective.

1.6 RESEARCH OUTPUTS

List of journal articles from this research:

Makhoba X. & 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 DOI: http://dx.doi.org/10.1080/20421338.2016.1147205

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Makhoba X, Pouris A (2019). A patentometric assessment of selected R&D priority areas in South Africa, *World Patent Information*, 56, 20-28 DOI: https://doi.org/10.1016/j.wpi.2018.10.001

1.7 OVERVIEW OF STUDY

The rest of the thesis will look as follows in terms of chapters:

Chapter 2 gives an introduction to the South African public R&D landscape and R&D priority areas

Chapter 3 gives a literature review on the relevant theories, scientometric assessment indicators and data sources.

Chapter 4 provides the details on the methodologies used for the study of the R&D priority areas.

Chapters 5, 6, 7 and 8 detail the results of the evaluation, through bibliometrics and patents data, of the selected R&D priority areas with the comparison to the BRIC countries.

Chapter 9 provides the conclusion, summarising the findings of the study, identifying the limitations and areas of future research.

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CHAPTER 2 CONTEXT OF THE STUDY

Relevant literature was consulted to establish the main policy issues with South Africa and the reference to the BRICS grouping. The institutional arrangements in South Africa are discussed and previous studies that mention these research areas or comparator countries are highlighted.

2.1 SOUTH AFRICA AND OTHER BRICS COUNTRIES

2.1.1 South Africa and institutional arrangements

The Department of Science and Technology (DST) is the government ministry responsible for development of policies as well as government intervention in science and technology in South Africa. The government additionally has science councils that conduct research in specific areas according to their mandates. There are numerous research councils; some are sector-specific, concentrating on a specific sector such as agriculture, water, mining or medical research. One that conducts generalised industrial research is the Council for Scientific and Industrial Research (CSIR), which falls under the responsibility of the DST and tends to focus on the areas that are regarded as important according to government policy. In addition, there are also funding agencies that provide for research. An example of such a funding agency is the National Research Foundation (NRF), which funds early stage research mostly at universities. The NRF additionally houses national facilities that conduct research in their own right. These include the iThemba LABS that conduct nuclear research, particularly nuclear medicine and the South African Astronomical Observatory (SAAO), which is a national facility for astronomy. In addition to these, there are currently 23 established public universities in South Africa that conduct research with varying emphases, in addition to their teaching responsibilities. The most prominent of these in terms of the world rankings, are the University of Cape Town, University of Witwatersrand, University of Pretoria, Stellenbosch University and University of KwaZulu-Natal (Matthews, 2012).

2.1.2 The BRICS previous scientometric studies

The BRICS have previously been studied by several authors to compare performance of countries within the group. Some studies have considered the scientific outputs (Bornmann, Wagner, & Leydesdorff, 2015), collaboration within the grouping (Finardi, 2015), and the comparison with other country groupings (Yi, Qi, & Wu, 2013). Additionally, studies where countries in the same grouping are compared are common practice; for example, studies have been done looking at the Organisation for Economic Co-operation and Development (OECD), EU27 and Association of South East Asian (ASEAN) countries. The reason for the choice of the BRICS in this context is that South Africa belongs to the grouping and BRICS countries have been working towards closer cooperation between the members, within the scientific disciplines specifically. It must be pointed out that the focus of this paper is on the performance of South Africa in its priority areas, while the other BRIC countries are used for comparative purposes only.

Other studies that have been carried out amongst the BRICS countries include the work of Singh and Hasan (2015). This study considered the total research output by the BRICS countries; it found that this grouping produced 10.67% of the world's scientific output in the 20-year period between 1994 and 2013. The authours also found that the grouping has increased its share of publications globally from 1.51% in 1994 to 12.43% in 2013. A study of this country grouping by Bouabid, Paul-Hus, and Larivière (2016) found that the level of scientific collaboration and high technology exports between the BRICS and the G-7 countries (Canada, France, Germany, Italy, Japan, UK and USA) has increased enormously. However, Bouabid *et al*. (2016) found that both the intra-BRICS high-technology flows and the intra-BRICS scientific collaboration have very weak. Finardi and Buratti(2016) conducted a study to do an in-depth analysis of scientific collaboration based on coauthorship between the BRICS countries with similar findings. It is therefore clear that while there are some positive signs the BRICS grouping has not reached the desired level of scientific collaboration.

Considering previous work, Bornmann et al. (2015) found that the BRICS countries, with the exception of Russia, have increased their output in terms of most frequently cited papers at a higher rate than the top-cited countries worldwide. While that study did not have a specific focus on the areas as considered here, their analysis is in line with the findings presented in this paper. Yi *et a*l. (2013) compared the performance from a scientometrics perspective of the BRIC (Brazil, Russia, India and China) and CIVETS (Colombia, Indonesia, Vietnam, Egypt, Turkey and South Africa) groups, which are both viewed as promising emerging economies. Using some knowledge-based economy indexes, such as knowledge economy index, and some scientometric indicators, such as disciplinary specialisation index, the authors found that that there was no significant difference between CIVETS and BRIC in knowledge-based economy performance, scientific research quality and scientific research structure. Finardi (2015) also conducted a study on the scientific collaboration between the BRICS countries, emphasising that these countries have discussions on scientific and technological collaboration as part of their summits.

Further, most of the studies based on patent statistics have largely focused on developed countries, while less developed and developing countries have remained unrepresented in a study of India and China patenting trends within the US system. Interestingly, both countries are undergoing technology-based growth and tend to compete in many sectors. Both countries tend to patent their inventions in the US, as it is their main export market (Bhattacharya, 2004). This shows the dependence of developing countries in advanced countries not only for finding markets for their inventions but also as a source of knowledge. In a study in Brazil, using the data collected from the country's patenting authority, the National Institute of Industrial Ownership (INPI), it was found that most of the patent documents tend to cite knowledge produced in other countries with the US representing more than 50% of such information (Pereira & Bazi, 2009). This highlights the relatively small base of infrastructure for scientific and technological production of researchers in developing countries.

2.2 SCIENCE POLICY IN SOUTH AFRICA

South Africa is the biggest producer of patents and publications in the African continent; it is therefore in a unique position among this group of developing countries. The output in terms of publication from this country comprises a third of all publications produced from the African continent (Tijssen, 2007). As it has been established previously, publications are widely used as a measure of R&D performance of countries; however, when it comes to innovation, the picture is not as obvious. In the following subsections we look at the country's technology policy and the priority areas to be studied.

2.2.1 R&D strategy & focus areas

It is worth noting that it has set itself several priority areas, as articulated in the country's National R&D Strategy (DST, 2002) and the Ten-Year Innovation Plan (DST, 2007), as well as several discipline-specific strategies and frameworks. The country tends to prioritise areas where it has a geographic advantage, such as astronomy, palaeosciences, Antarctic research and biodiversity. Additionally, the country also targets areas that will stimulate industrial growth, such as biotechnology and energy. The key areas further emphasised through discipline-specific strategies considered in this study are the National Biotechnology Strategy (DST, 2001), as well as the Palaeosciences Strategy (DST, 2012). These relate to a response to special social challenges or as areas that offer opportunity based on the country's strengths and/or geographical advantage. Such priority areas are viewed as central to the achievement of national goals, including enhanced economic growth, industrial competitiveness, as well as social and developmental aspirations (Kaplan, 2004). The aim of the first part of the study, therefore, is to focus on two areas that relate to enhancement of industrial competitiveness (energy and biotechnology) and the two other areas that are based on geographical advantage (astronomy and palaeontology). It is hoped that this will add to the literature demonstrating the use of bibliometrics, specifically the use of indices for comparison and measuring scientific progress.

Looking briefly at the focus areas, biotechnology has received a lot of attention because it has many potential uses and significant commercial benefits in areas such as provision of health products, alternative fuels and improving food production. Biotechnology as a priority area predates the R&D strategy; the biotechnology strategy was published in 2001 while the R&D strategy was published a year later. This shows that the country views this area as very important indeed. The Biotechnology Strategy was aimed at initiating the development of technologies and associated products and services to address the vital science-based innovation needs of the country in the health, industrial and agricultural sectors of the economy. The government further launched a Bioeconomy Strategy in 2013 that was broader in scope, focusing on agricultural, health, industry and environmental sectors of the economy. These are the main policy drivers of the biotechnology investments by the government in the country. South Africa has been interested in alternative energy for a while, for example, the Department of Energy (which was then a Department of Minerals and Energy) published a biofuels strategy (2007) through which it encouraged production of biodiesel and bioethanol for inclusion in automotive fuels, through fuel levy exemptions. In addition, the White Paper on Energy Policy (1998) acknowledged the importance of alternative energy and a diverse energy supply. Additionally, South Africa has an energy-intensive economy with most of the primary energy derived from coal. As a result, the country has high emissions of greenhouse gasses per capita. In fact, in some cases, it is higher than some European countries; as a result, energy efficiency and development of alternative energy is an important focus for the country (Winkler, 2007). The research and development in the information and communications technology ICT is guided by the Information and Communication Technology Research & Development and Innovation Strategy (2007) driven by the DST. Amongst its goals is the need to develop and broaden participation in ICT by entrepreneurs from historically disadvantaged population groups, rural communities and the knowledge-intensive industry. The strategy does identify some weakness such as a relatively low R&D expenditure in ICT in the country and the low level of Internet and broadband penetration. The strategy had a vision of addressing this over the long term.

In terms of astronomy, South Africa has developed the infrastructure to enable astronomy and space physics research, investing in facilities such as the Hartebeesthoek Radio Astronomy

Observatory for radio astronomy and space geodesy, the Hermanus Magnetic Observatory for geomagnetism and space physics, as well as a facility in Antarctica (Martinez, 2008). Martinez (2008) further notes that it is due to these investments that the country has been able to attract big international projects in astronomy, such as the Square Kilometre Array (SKA). Investments include the MeerKAT radio telescope, based in the Northern Cape, and its predecessor, the seven-dish Karoo Array Telescope (KAT-7). The MeerKat will be integrated into the SKA on its completion. Another investment in this field includes the establishment of the Southern African Large Telescope (SALT), which is the largest single optical telescope in the southern hemisphere and among the largest in the world. In terms of palaeontology and astronomy, these fields are well recognised for their ability to attract the attention of young children to science, particularly due to their ability to “capture popular imagination” (DST, 2012). In addition, these fields are further emphasised due to the country’s geographical advantage; South Africa has some of the best evidence in the world of how plant and animal life has developed. Therefore, it became critical that the country invests in developing the human capital to protect the fossil heritage and build expertise in palaeosciences.

Nanoscience and nanotechnology (N&N) is now widely recognised as an area of science and technology that promises to bring many scientific breakthroughs in the coming years, and this will have a meaningful impact on the economy. According to Lux research (2015), the revenues from nano-enabled products worldwide, as of 2014, stood at $1.6 trillion, having grown from $850 billion in 2012; a 90% growth in two years. The application of nanomaterials is across so many different applications, such as cosmetics, construction materials, for example in paints, as well as electronics, the figure includes all these applications. It is important to note, as Reis and Thielmann (2010) pointed out, that nanotechnology does not constitute a product specifically, but is, in most cases, integrated in a large variety of different applications in many industrial sectors. It therefore can be understood as an enabler of innovative technologies and applications by substituting and improving existing products or leading to fundamentally new products (Reis and Thielmann, 2010). As a result, various governments have been investing in the development of nanotechnology in their respective countries.

The OECD defines nanotechnology as a set of technologies that enable the manipulation, study or exploitation of structures and systems of typically less than 100 nanometres in size. It is believed that developments in N&N have the potential to affect virtually every area of economic activity and aspect of daily life (OECD, 2014). This is due to the technology's ability to contribute to the development of novel materials, devices and products. The number of products, and the diversity of nanomaterials and nanosystems, is predicted to increase rapidly in the coming decade as a result of continuous innovation in many sectors. These can be applied in many commercial products in areas such as health, especially drug-delivery, energy, food packaging and water purification systems. It is evident that no work done to evaluate the development in this field since the N&N strategy was introduced in South Africa. In this study, the aim is to establish publication and citation trends, in the second part the collaboration and the most productive countries and institutions, and finally at the intellectual structure of the nanotechnology research in terms of subject area. The investment in N&N research, along with other areas, is seen as a means to moving towards a creation of a knowledge-based economy, and as such, it is important how the country is progressing in this regard. In terms of terminology, nanoscience and nanotechnology are used interchangeably throughout the article, as is practice by the research community.

2.2.2 Nanoscience and Nanotechnology in South Africa and some developing countries

Based on potential economic benefits and developments internationally, the South African government made some policy interventions to stimulate the development of this technology. This was done after the establishment of the Nanoscience and Nanotechnology strategy (2006) with the stakeholder community under an organisation called South African Nanotechnology Initiative (SANI). The goals of the strategy were to "support long term research that will lead to the fundamental understanding of nanomaterials" and a more ambitious target of supporting the "creation of new and novel devices for application in various areas, such as health, water and energy". To support these objectives, the government made several investments including among others:

- The establishment of the Nanotechnology Innovation Centres with a mandate to build the capacity to develop commercial nano-enabled products. Two of these centres were established, with one based at Mintek and the other at the Council for Scientific and Industrial Research (CSIR). Both institutes are situated in the Gauteng province.
- Providing ring-fenced grants to researchers through the National Research Foundation (NRF) for purchase of nanotechnology-related research equipment under the National Equipment Programme funding instrument.
- Initiating and funding the establishment of a taught Master's degree programme in N&N, which is currently offered by four universities – the University of the Western Cape (UWC), Nelson Mandela Metropolitan University (NMMU), the University of Johannesburg (UJ), and the University of Free State (UFS).

These initiatives and other investments need to be contextualised, since South Africa entered the N&N field quite late compared to the developed economies. Government support through policy intervention and funding in this field is acknowledged (Claasens & Mokutu, 2006). Therefore, while the investments were well considered, they may not have been sufficient to allow South Africa to play a leadership role in this research area. Research done by Pouris (2007) indicated that the number of articles produced in South Africa had increased from just 12 in the year 2000 to 57 by 2005, with the University of Witwatersrand being the leading producer in this field. Pouris (2007) further highlights the absence of science councils at the time in the top producing category, with research largely driven by individual academics rather than a coordinated national approach. The findings from that study were also that the USA was a top collaborating country with South Africa. It is further noted that the number of N&N core journals currently indexed by the SCI is now at 83, this has been increasing steadily since the area started gaining recognition in the 1990s.

Looking broadly at the participation of African researchers in nanotechnology, it has been noted that participation is very low and fragmented. Generally, the growth in nanotechnology in the least developed countries, including Africa, has been very slow. While individuals have shown interest in this field, there is no practical plan for the advancement of this field, and as a result, nanotechnology remains an area of academic research (Ezema, Ogbobe & Omah, 2014). This study by Ezema *et al*. (2014) further points out that when looking at the developing countries, the BRICS nations produced a substantial number of publications, and outside this grouping, especially in Africa, there is very little activity. This is partly due to a lack of research infrastructure and facilities to carry out N&N research, and thus these nations are classified as nanotechnology dormant. Maclurcan (2005) points out that there are niche areas within N&N that are of benefit to the developing countries, for example, India and South Africa because of their high prevalence of tuberculosis (TB) infections have programmes for developing nanotechnology enabled TB diagnostic kits and improved TB drug delivery systems. This provides a clear niche area for these countries to establish competitive expertise due to their unique circumstances.

2.2.3 Patenting in South Africa

In a developing country such as South Africa, inventors tend to prefer to file their most promising patents in foreign jurisdictions, such as the United States, through the USPTO or Europe, using the EPO. This is most likely due to fact that South Africa, for example, is a non-examining patent office, which has its disadvantages. Pouris and Pouris (2011) pointed out that in such a system, the responsibility for ensuring that the validity of the application resides with the applicant. This means that Companies and Intellectual Property Registration Office (CIPRO), now called Companies and Intellectual Property Commission (CIPC), does not investigate the novelty or inventive merit of the invention, meaning that only the forms or documentation are verified and not the substance of the product or process. This is a major departure from the international norm in developed countries where the applicant is required to prove that the invention has some function, is novel and not obvious to a person skilled in that field. South Africa therefore does not have examiners to safeguard the quality of invention it registers. This creates certain undesirable market behaviour such as, broadening the scope of the patent, multinationals applying for and being granted patents that would not be granted in their home countries. This makes the South African system one of the cheapest in the world with the resultant proliferation of frivolous patents and exploitations by foreign interests, according to Pouris and Pouris (2011). This is no different from other developing countries in general; a similar trend was found, for example, in Malaysia. A study by Govindaraju & Wong (2011) looked at the developing countries, with specific reference to Malaysia, using the Malaysian and the US patenting system, and found that patenting activity is increasing, with most of the patents coming from foreign firms in that country, as is the case in South Africa.

To encourage the protection of intellectual property and intellectual property rights that have been created with public funds, the DST established the National Intellectual Property Management Office (NIPMO). NIPMO was established through the Intellectual Property Rights from the Publicly Financed Research and Development Act (2008) and supports the establishment of technology transfer offices in South African research institutions. These, in turn, enable the protection of the IP created from the research. It is envisaged that the establishment of these technology transfer offices will. amongst other things, enable the increase in patenting activity in South Africa.

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CHAPTER 3 THEORETICAL BACKGROUND

In this chapter, relevant theoretical background is given and some of the concepts that are used to drive the research question. Literature was consulted to establish the key issues with scientometrics, and specifically the application of patents and publications, and the methods used for the delineation between the different fields of science. The findings from previous studies are also discussed, where these include South Africa, the research areas or comparator countries.

3.1 TOWARDS A THEORETICAL FRAMEWORK

Science of science is a research field that looks at developing theoretical models, for better understanding, the qualitative and quantitative aspects of scientific venture, ultimately scientometrics, falls within this area of research. Scientometrics concerns the study of scientific progress, and therefore, the holistic understanding of the whole knowledge-creation process is needed before an assessment is done.

3.1.1 Models for the analysis of a system of innovation

In developing the conceptual framework for analysing the outputs from the priority areas, we look at a few pre-existing models as a frame for the analysis of relationships between the different actors within the so-called system of innovation. Innovation system emphasises the linkages and the flow of information between the different actors during the innovation process. Then, we look at some of the models that demonstrate the link between research and the technology-based innovation. In this thesis, a few of the common models are considered; the linear model of innovation, the chain linked model of innovation, and the less common but applicable Techno-Economic Network (TENs) model. It starts with the linear model of innovation [Figure 1]. This model assumes that research is followed by development, production then marketing, in a sequential fashion.

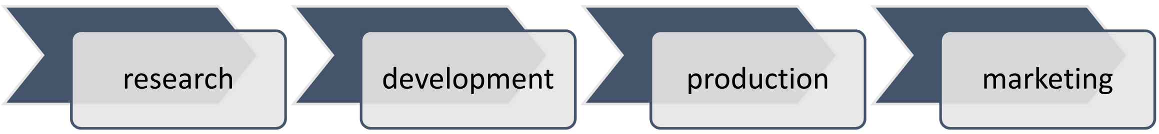

Figure 1. Linear model of innovation

The chain linked model of innovation, made popular by Kline & Rosenberg (1986), recognises that the process of innovation is not necessarily linear but is interactive, relying on both the development process and the feedback from the market [Figure 2].

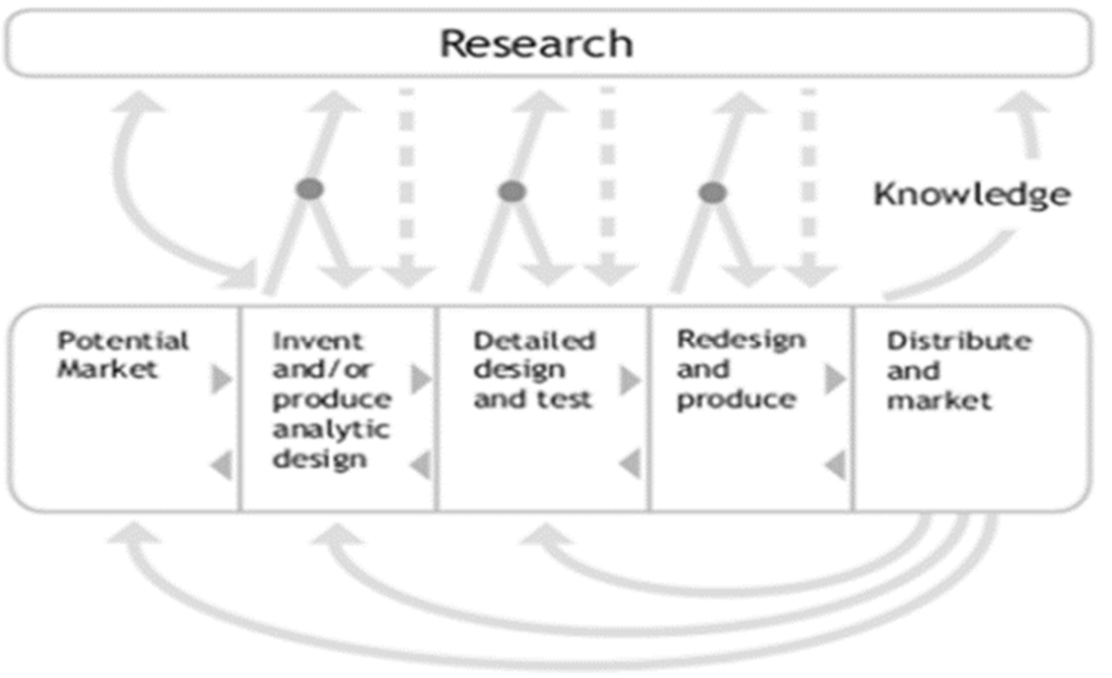

Figure 2. Chain linked model, an interactive model of the innovation process

Source: Kline & Rosenberg (1986)

In the TENS model, innovation is largely dependent on the coordination of distributed knowledge among the different actors in the network. Performance is determined by the differences between the structures of both networks, and demonstrate that these differences are related to how the actors are integrated. The conceptual framework shows the linkages between the outputs and government policy in simple terms. Perhaps a more applicable model is to apply the concept of Techno-Economic Networks (TEN), made popular by Callon (1990), and other proponents of the actor-network approach. It is described as a kind of organisational form resulting from links between a variety of heterogeneous actors such as university laboratories, technical research centres, financial organisations, users, as well as the government (Hull, Walsh, Green & McMeekin, 1999).

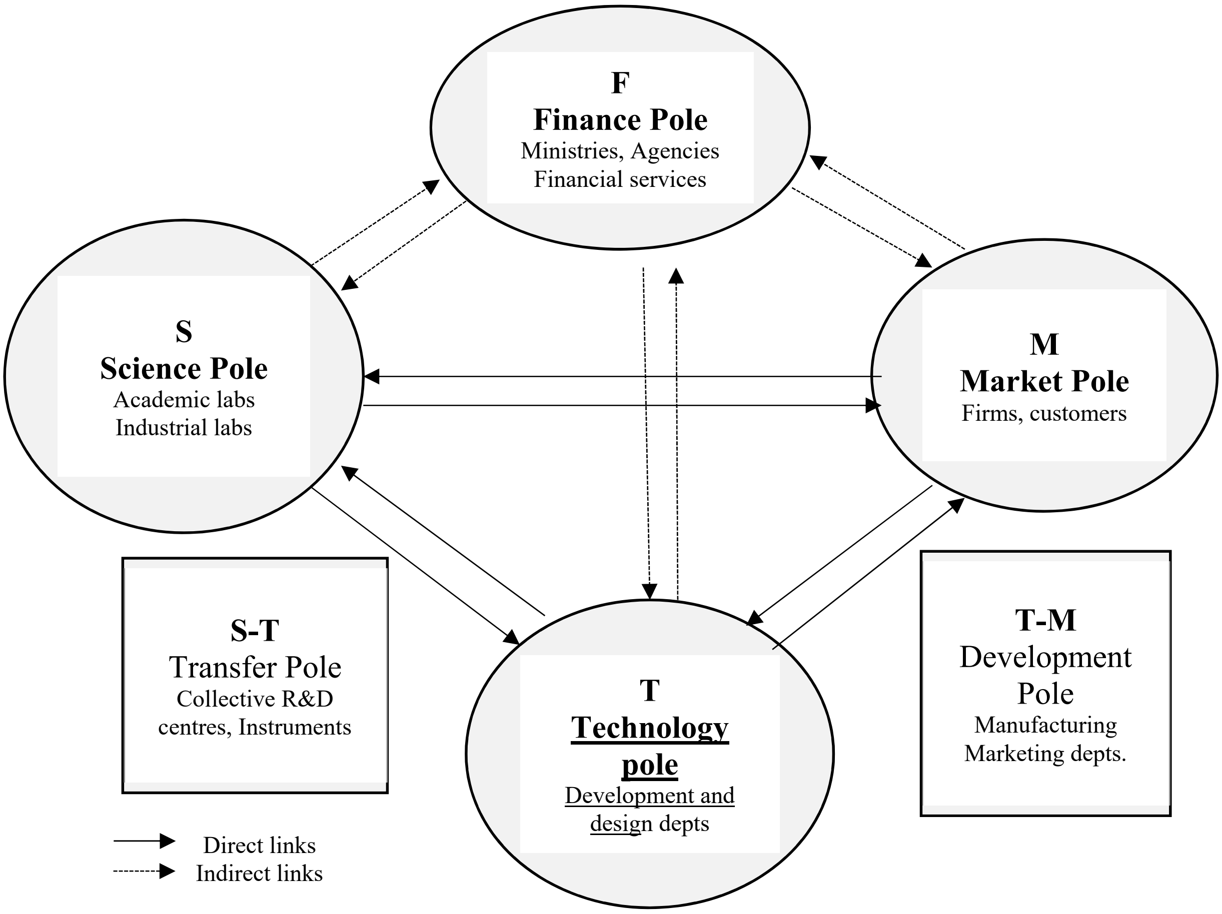

Figure 3. Techno-economic network (TEN) framework

Source: Hull, Walsh, Green, & McMeekin (1999)

Another framework that illustrates the roles and linkages of actors is the techno-economic network, with roots in sociology [Figure 3]. This is a useful framework to analyse the systems of innovation in a comprehensive manner for a chosen sector (Callon & Bell, 1991). There are three major poles within the TEN, the technology pole, the science pole and the market pole. Another minor pole that appears within this framework is the finance pole, due to its indirect players or links to innovation. Each of these poles is categorized by the type of actors and intermediaries regarding its duties. As illustrated in Figure 3, intermediaries vary in terms of tangible and intangible resources for those actors within TEN. Moreover, it presents how these poles are linked to each other in terms of their direct or indirect linkage and which intermediaries they are linked by, such as the transfer pole (between the science pole and the technology pole) and the development pole (between the technology pole and the market pole). The TENs model presents a dilemma in that it implies that there is weak linkage between the finance pole with innovation. If this is indeed true, it represents a challenge, as it will mean that the government policy and the associated instruments have very limited impact on the innovation outcomes.

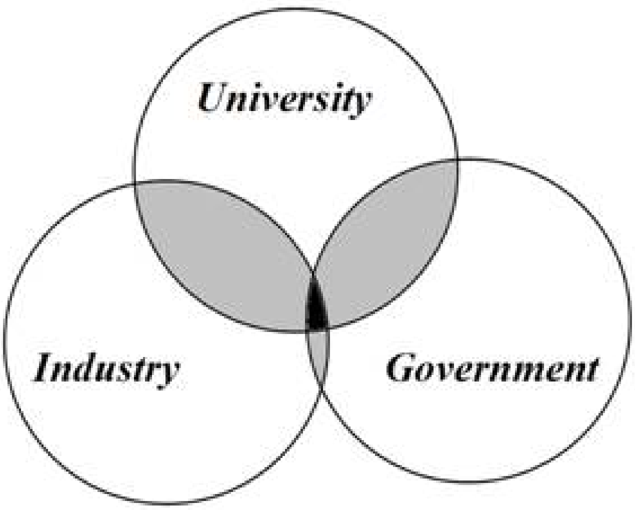

Figure 4. The triple helix model

Source: Etzkowitz & Leydesdorff, 2000

Advances in innovation theory in recent years have gradually moved closer to a fully systemic, dynamic, non-linear process involving a range of interacting actors. This is, in addition, demonstrated by the triple helix model in [figure 4], which emphasises the knowledge flows between actors; expectations about future technology, market and policy developments; political and regulatory risk and the institutional structures that affect incentives and barriers. The triple helix (Etzkowitz & Leydesdorff, 2000; Leydesdorff, 2012) proposes a three-pillar model where academia, industry and government work together to enable innovation. Government provides innovation policies, finance, especially for basic research, as well as establishing incentive programmes to encourage innovation. The academia provides the human capital needed for innovation by training undergraduates and postgraduates, as well as basic technology coming out of academic research activities. The industry brings with it market expertise and capital to translate basic technology to market products. The triple helix emphasises the interdependencies between the three actors.

Thus, while the specifics of the conceptual and methodological framework may vary, these more recent innovation systems approaches tend to emphasise the role of multiple agency and distributed learning mechanisms in technological change. Rather than all-powerful firms or unidirectional knowledge flows, the focus is on inter-organisational networks and feedbacks. The system perspectives still acknowledge the existence of stages of technology development, but they attempt to put these in a wider context. In particular, the role of institutions, at all levels, in establishing and maintaining the boundaries to prevent change that is more radical. The importance of feedback between various parts of the system is also emphasised, as are the links between technological and institutional change. A well-functioning system vastly improves the chances for technology to be developed and diffused.

Therefore, while the government, in this context, may come up with national policies that encourage research towards the realisation of national R&D priorities, it does not have a direct control of the implementation. The implementation relies on the other actors within the system, such as the autonomous universities and science council, and private businesses.

These actors are likely to implement the policies if they are in line with their own objectives and/or there are other incentives to do so. Governments normally use the funding mechanisms as a way of encouraging research in a particular direction and, of course, this comes with its own challenges (Egilman & Bohme, 2005). The priority setting is viewed with suspicion, as the use of funds may emphasise certain research over the other and may lead to flawed analyses and manipulation of results to meet a desired outcome. Egilman & Bohme (2005) further lament a case of environmental research and the associated funding of research by corporates in this field that is normally biased. This observation is particularly applicable in cases that involve government funding in a setting where a stance has been decided on politically contentious matters, such as climate change. Accordingly, stakeholders are normally wary of the finance pole and agenda that it may be trying to push in a particular direction, while stifling funding for research in alternative viewpoints.

The models presented provide very useful tools for the analysis of an innovation and for the identification of issues where the system is not operating optimally; these will provide a framework for reflection when the results are analysed later on.

3.1.2 The research philosophy

To understand the R&D process, there is a need to consider the relationships between the inputs and outputs. Firsty how does one define research and experimental development? one The definition according to the OECD's Frascati manual is that it is a "creative and systematic work undertaken in order to increase the stock of knowledge and to devise new applications of available knowledge." The definition encompasses three types of activity; basic research, applied research and experimental development. In addition, the manual stipulates that for an activity to be an R&D activity, novel, creative, not obvious, concepts and hypotheses, uncertain, systematic and transferable and/or reproducible.

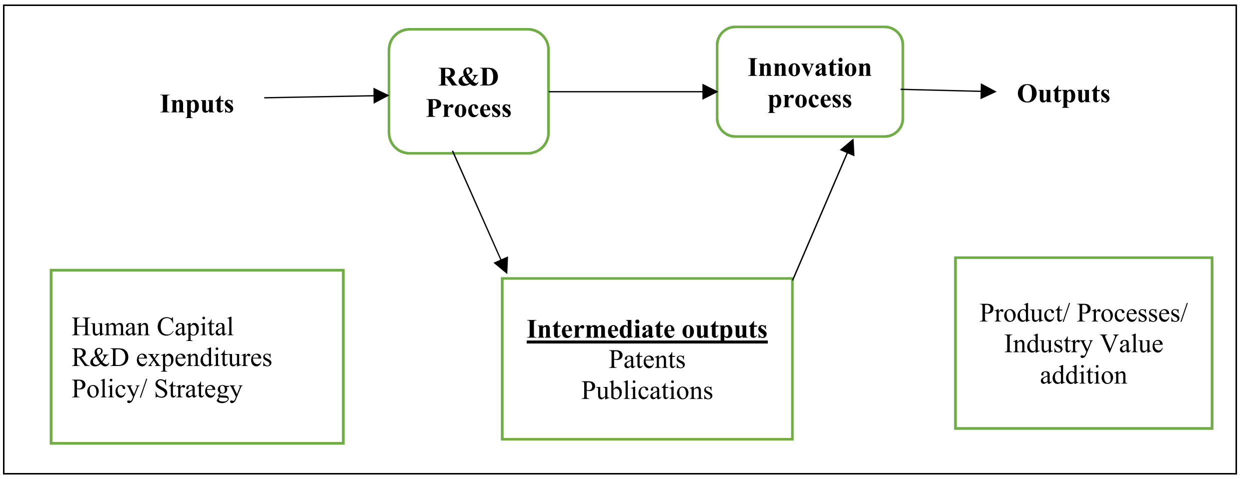

Figure 5. A simplified conceptual framework for the innovation process in an innovation system

Figure 5 highlights the important steps in the R&D process and the R&D based technological innovation. It highlights that patents are intermediate products in the innovation process but a very direct measure of outputs in the R&D process. The R&D process is, of course, divided into two sub-processes; the knowledge production process and the knowledge commercialisation process. The outputs from the knowledge production process can be processed further to enable the commercialisation of the knowledge generated. As well established as that is in the R&D process, the R&D expenditure is not the only input, and patents and publications are not the only outputs. Some of the other inputs are manpower availability and policy, and the other outputs are as represented in the diagram, such as spin off and profits applicable in the private sector. While this research considers the outputs from the knowledge creation process, patents and publications, it is understood the government's policy is knowledge commercialisation. This will contribute to other government policy objectives related to economic development, such as creation of new products, industries and job creation.

3.2 SCIENTOMETRICS

In this section, the broad area of scientometrics is discussed as a research area. The definitions, the applications and some of the pitfalls are pointed out. This chapter begins by definitions in terms of the state of the art, in terms of scientometrics and related studies in this field. The chapter then follows course in South Africa's R&D evaluation and assessment and the BRICS in general terms. Several scientometrics indicators relevant for the scenario where the output from the priority areas is being compared to one another and the output from one country is compared to that of other countries with very different size (GDP, population and science system).

3.2.1 Bibliometrics, Scientometrics or Informetrics

Scientometrics falls within a broad area of informetrics, when sometimes confused with bibliometrics. Scientometrics is the science of understanding quantitative aspects of science research. In practice, scientometrics is often done using bibliometrics, described as a quantitative study of written output of science (Van Raan, 1997) and is used widely to understand the publication profile of different scientific disciplines and measure the impact of (scientific) publications. Bibliometrics is sometimes referred to as the evaluation of science through bibliographic statistics; the earliest definition that is widely accepted is by Pritchard (1969), which defines bibliometrics as the application of mathematics and statistical methods to books and other media of communication. Hood and Wilson (2001) published an informative literature review on the differences between bibliometrics, scientometrics and informetrics. They rightly point out that the term bibliometrics is sometimes used for all the three metrics. The three metrics are quite closely related but are not the same thing. Scientometrics refers to the study of the literature of science and technology. The argument is that much of scientometrics is sometimes indistinguishable from bibliometrics and much of bibliometrics research is published in the *Scientometrics* journal, for example. The *Journal of Informetrics* also publishes bibliometrics, scientometrics, webometrics, and altmetrics so the fields are, by definition, closely related. Indeed, there is more to scientometrics than just studying and analysing research output in terms of publications. Other issue that are of interest to scientometrics practitioners include technology diffusion, R&D expenditures and funding, as well as impact of government policies.

There are certainly other related metrics , such as webometrics and cybermetrics, that are out of the scope of the study but can be applied to the study of technology. While some consider webometrics as a subfield of cybermetrics, cybermetrics refers to the study of the web, while webometrics refers to the studies of all internet applications; all these are part of informetrics (Bar-Ilan, 2008). Altmetrics seek to propose alternative ways of measuring impact away from traditional citation-based measures; examples include the use of the article or discussion in social media, blogs or policy documents. It is an approach to finding previously invisible traces of scholarly impact by observing activity in online tools and systems (Priem, 2014). Informetrics is the study of the quantitative aspects of information in any form, not just records or bibliographies, and in any social group, not just scientists (Egghe, 2004). Patentometrics is similar to bibliometrics in that practitioners use patents data to study technological development. While this study does fall within the informetrics family that includes scientometrics, the focus will be on patentometrics and bibliometrics applied within the scientific context, hence the title refers to scientometrics.

When measuring the performance of a scientific system, it is important to consider that there are input indicators and output indicators. Publications are output indicators, especially for basic and applied science (Wagner-Döbler, 2005). This is important, as the use of an inappropriate indicator will give results of no practical significance. Another aspect to consider is normalisation. Normalisation is a necessity, especially in cases where different disciplines are compared, since communication behaviours differ considerably among various subject fields (Glänzel & Moed, 2013). An additional but very important issue is the unit of analysis when it comes to publications, as there can be various alternatives where more than one researcher, or researchers, from more than one institution or country, author the publication. There are three widely accepted counting methods, namely, whole counting, fractional counting, and first author counting (Larsen, 2008). According to Larsen 2008, in whole counting, all unique countries, institutions or authors contributing to a publication receive one credit.

Leydesdorff and Gauthier (1996), while assessing the performance of the countries that have advanced materials and biotechnology as priority areas, expressed some concerns that various countries tend to make similar choices in terms of priority areas. According to Leydesdorff and Gauthier (1996) this is especially common amongst the OECD countries. Another problem identified in scientometric research is the classification and delineation of fields, for example, the definition of biotechnology differs slightly between different regions, including which areas it encompasses. The authors further state that delineation using core journals, as done by the Thomson Reuters Web of Science classification (WoS), may not account for research published in multidisciplinary journals. Delineation is achieved by using keywords to extract the relevant publications from the database; another technique is content analysis or using only core journals.

It has been mentioned that bibliometrics analysis will be performed on the data obtained from a citation index database. Garfield (1964), the founder of the Science Citation Index (SCI), defines a citation index as an ordered list of cited articles, each of which is accompanied by a list of citing articles. The most commonly used academic citation index used in bibliometrics research is the Thomson Reuters Web of ScienceTM (WoS), formally Institute of Scientific Information. It must be noted that this citation index does not cover a majority of journals but relies on selected prominent journals and on cumulative advantage distribution as described by the Bradford's law of journal use, the Lokta law of distribution and the Pareto principle of income distribution (de Price, 1976). A simplified interpretation of the cumulative distribution model is that the most important literature for any subject field is likely to be found in a small collection of publications.

As mentioned earlier, bibliometric indicators have been used extensively to measure the performance of research output in different fields, including evaluation of institutions, research area, countries and regions. Publication and citation counts provide a simple tool for determining research activity in a field within a country, such as South Africa in this case. However, in cases where the study involves different subject fields, comparison of a number of publications across different scientific disciplines may be misleading, as different disciplines have different publication patterns. A useful indicator may be South Africa's share in the particular discipline or the activity index. The activity index takes into account the size of the country's science system. It was used first by Frame (1977) and is considered to be one of the classic scientometric indicators. This indicator is related to the revealed comparative advantage index that measures specialisation in economics, as described by Balassa (1965). It has been used previously used to measure the performance across different subject fields or countries (Frame, 1977; Schubert & Braun, 1986). Pouris (2010) used the activity index in comparing the science output in Southern Africa Development Community countries.

The activity index, according to Frame (1977), is the ratio of the country's share in the publication output in the field to the country's share in the world's publication outputs in all fields. According to Schubert and Braun (1986), it is the ratio of the given field's share in the country's publication output to the given field's share in the world's publication output. Another important measure is the attractivity index that, according to Schubert and Braun (1986), is defined as the ratio of a country's share in citation attracted by publications in a given country's share in citations attracted by publications in all science fields. This will then also allow for a comparison of relative impact of different scientific fields. The WoS and InCites^{TM} analytical tools do not report the activity or the attractivity indices directly, but these can be calculated from the other statistics reported.

Activity index (AI) as described by Frame (1977);

Equation 1. Activity index

$$AI = \frac{\text{The country share in the publication output in the field}}{\text{The country's share in the world's publication output in all fields}}$$

Or equivalently Schubert & Braun (1986)

Equation 2. Activity index

$$AI = \frac{\text{The given field share of the country's publication output}}{\text{The given fields share in the world publication output}}$$

Equation 3. Attractivity index

And attractivity index (AAI);

$$AAI = \frac{\text{The countrys share in citations attracted by publications in the given field}}{\text{The countrys share in the citations attracted by publications in all science fields}}$$

Or equivalently,

Equation 4. Attractivity index

$$AAI = \frac{\text{The given field share in citation attracted by countries publications}}{\text{The given fields share in citations attracted by all publications in the world}}$$

The activity index (AI) indicates the country's relative share in world publications in a particular field of science to the overall share in world total publications, as described by Frame (1977) and extended by Schubert and Braun (1986). Attractivity index (AAI), as described by Braun, Bujdoso and Schubert (1986), characterises the relative impact of the country's publication in a given subject field as reflected by the citations they attract. It is worth noting that another indicator, the Relative Specialization Index (RSI), has been proposed as an alternative to the activity index but it has not received wide acceptance as it has been clearly proven to have some methodological problems associated with it, as highlighted by Stare & Kejzar (2014).

3.2.2 The applications and misuse

Bibliometrics has been used extensively as a quantitative measure of progress of research in specific countries (Jacobs & Ingwersen, 2004; Sooryamoorthy, 2010; Kahn, 2011; Pouris, 2007), in a selected region such as Africa or Southern Africa (Naravaez-Berthelemot, Russell, Arvanitis, Waast & Gaillard, 2002; Pouris & Ho, 2014). Bibliometrics has also been used to measure research progress against a set of priority research areas, such as the European Commission's FP7 priority areas (Hassan, Haddawy, Kuinkel, Degelsegger & Blasy, 2012; Leydesdorff & Gauthier, 1996). South Africa has certain characteristics that make it unique. For example, recently it has been invited to the BRIC grouping of countries, yet it has a number of developmental challenges. In terms of scientific output, it is well recognised that South Africa is a leading producer of research output in Africa, as measured by the total number of publications. Scientometric indicators have been applied quite extensively in measuring the performance of regions, countries, research institutions and individual researchers. A very useful tool for research managers, funders and policy makers for ranking of institutions and increasingly, individual researchers.

Alarmed by the abuse of the metrics, a group of prominent researchers formulated the so-called Leiden manifesto, in which they have tabulated the ten principles for the use of bibliometrics data for meaningful evaluation of research (Hicks, Wouters, Waltman, De Rijcke & Rafols, 2015). Their view is that while the metrics are useful in research evaluation,they do not replace the peer review process and should be used as a complement when rating individual researchers and institutions particularly. The authors caution against the overzealous application and reliance on metrics such as the H-Index, which were actually meant to assist the science, but often some of these well-intentioned efforts are ill-informed. The obsession of most universities with their rankings in relation to other universities worldwide based on several rankings, such as the Shanghai Ranking and Times Higher Education's list is a concern and, in addition, these lists are considered inaccurate by these authors. The ISI is biased towards the developed countries, particularly the formidable United States, and therefore, researchers who do social sciences research, which tends to focus on local issues in developing countries, will end up with a lower rating. It is obvious a blind application of the metrics, such as the bibliometrics and , as discussed in this study, will not help improve the performance of the system of innovation as the metrics may have led to some unintended behaviour and consequences. This has been extended to consider other social network-based metrics, such as the so-called RG score by ResearchGate, which has been found to be an unreliable indicator of scientific and academic reputation (Copiello & Bonifaci, 2018).

3.2.3 Bibliometric approach to priority areas

In this section, the approaches used for the selected priority area as well as any previous studies in the BRICS countries and South Africa are discussed. As previously mentioned that not all priority areas can be considered, a brief overview for each of only the priority areas studied, such as astronomy, nanotechnology, health, biotechnology, ICT, palaeontology and energy is given.

Bibliometric approaches are increasingly used for the assessment of scientific disciplines providing useful information for those who fund research. It is established that increased investment should lead to an increase in publications, this investment is also more positive if it is a public sector investment rather than private sector (Shelton, 2008). Bibliometrics is defined as the application of mathematics and statistical methods to communication media. Bibliometrics have been used extensively to evaluate research progress quantitatively. Bibliometrics have been applied, for example, in studying research output for specific countries and regions (Darvish & Tonta, 2016; Sooryamoorthy, 2018; Kahn, 2011), in a continent or a region such as Africa or Southern Africa (Confraria & Godinho, 2015; Pouris A & Ho Y.-S, 2013), or sometimes for a research discipline such as nanotechnology (Lavrik, Busygina.

Shaburova & Zibareva, 2015, Pouris 2007), or even a single institution (Chiware & Skelly, 2016). One problem identified in bibliometric research is the classification and delineation of fields, for example, for new and emerging areas like biotechnology and nanotechnology, the definitions differ between different application areas, including which areas it encompasses. Leydesdorff (2008) further states that delineation using core journals, as done by the Thomson Reuters Web of Science classification (WoS), may not account for research published in multidisciplinary journals. In areas such as these, delineation is achieved by using keywords to extract the relevant publications from the database, as in this case. Another approach is content analysis or using only core journals, or a combination thereof. In a multidisciplinary area like N&N where literature is scattered, delineation is more important and only keywords are able to extract the relevant publications since there are relatively few established core journals, and the literature tends to be published in traditional journals such as those in the fields of chemistry and physics.

Looking at some of the previous related studies, one study by Molatudi & Pouris (2006) that looked at biotechnology in South Africa came to an observation that the biotechnology research base in South Africa is very small compared to the world. The study concluded that the lack of adequate output in the core biotechnology disciplines (microbiology, genetics and molecular biology) poses a threat to government policies and investment aimed at increasing biotechnology commercialisation. In terms of energy, Pouris (2016) also recently conducted a bibliometrics study on the energy landscape in the country, in which it was found that energy research is increasing, albeit from a very low base. This field also showed an overall lower level of collaboration with other countries compared to the other fields in the country. These two observations paint a lacklustre picture for the research activity in the priority areas.

There is not a lot of work that has been carried out in the area of astronomy, much less in South Africa. One related study in a developing country that could be found is that conducted in Turkey for the period 1980–2010. Here the researchers (Bilir *et al*, 2013) found that the astronomers in this country have increased the number of publications as well as citation in this field. However, Turkey, when compared to OECD countries with similar economy, was not doing so well. The other study done by Chang & Huang (2013) identified South Africa as having one of the top 50 astronomy institutions in the world. Amongst the other BRICS countries, only China and Russia had institutions featured in this top 50. There is very little scientometrics research in terms of the earth sciences, and specifically palaeontology, which is a small field within the broader earth sciences. One study by Racki (997), looking at the coverage of palaeontology by the Science Citation Index, observed that palaeontology is one of the smallest of the 150 fields covered by SCI and does not generate as many articles or citations as other areas, for example, biochemistry and molecular biology.

In this study bibliometrics analysis was performed on the data obtained from a citation index database. A citation index is defined as an ordered list of cited articles, each of which is accompanied by a list of citing articles (Garfield, 1964). There are many academic citation indexes used in bibliometrics research, such as CiteSeer, Google Scholar and Elsevier's Scopus, depending on the context of the study, but the most commonly used is the Thomson Reuters Web of ScienceTM (WoS). Importantly, when the two most commonly used databases, Scopus and WoS, were compared, it was found that the results between the two databases resulted in basically the same results when comparing disciplines at a country level (Archambault, Campbell, Gingras, & Lariviére, 2009).

3.3 USE OF PATENTS IN SCIENTOMETRICS STUDIES

Innovation is now accepted to be a major factor behind economic development and competitiveness for individual firms, regions, and nations (Tödtling and Trippl, 2005). In measuring R&D-based innovation, one has a choice between looking at the input indicators or output indicators. There are two most commonly used indirect methods that serve as proxy for innovation, they are R&D investments, which is an input indicator in the innovation process, as well as the patent data, which is an output indicator of innovative activity (Basberg, 1987). The measurement of innovation is an issue that has been studied quite extensively, with most studies correlating investments in innovation to financial wellness. However, patents have also been used to indicate the level of progress towards innovations, and in this study, the progress of development of a country's R&D priority areas is assessed using patents. Patents are used due to the wide availability of information across countries and regions. In addition, patents are an indispensable tool in the protection of intellectual property, particularly within the context of a knowledge intensive economy. This is important since a patent, by definition according to the EPO, is a legal title of industrial property granting its owner the exclusive right to exploit an invention commercially for a limited area and time. A patent therefore gives the inventor the right to stop others from, among other things, copying, using or selling such invention without authorisation. In return for the exclusive right to exploit it, the technical details of the invention are published. Novelty, inventiveness and industrial applicability of the invention needs to be demonstrated for a patent to be granted. It is important to note that a granted patent does not necessarily mean the product is safe for consumers use, for example, the medicines will still need to go through the medical trials and approvals, and proven safe for use before it can be made available in the market.

As much as South Africa is acknowledged as a leading producer of patents and publications in the African continent, it is less understood how the country is doing in relation to its strategic priority areas. The strategic priority areas discussed in this paper refer to areas that government has identified as deserving special attention and funding, with the aim of stimulating industrial development such as biotechnology, nanotechnology and others. Therefore, the purpose of this paper is to evaluate research performance in the selected priority areas using a quantitative angle of patent data. The focus is on the performance of South African research institutions in priority areas such as ICT, nanotechnology, biotechnology, space, energy and health. It is worth mentioning that the country has other science priority areas which, by their very nature, do not necessarily produce much patents; these include areas such as human sciences and palaeontology. As a result, this study will only consider those areas that are more readily patentable. A comprehensive list is contained in the Ten-Year Innovation Plan (DST, 2008) as well as other sector specific strategies of the country's National Department of Science and Technology. The bioeconomy and biotechnology, through the so called ‘Farmer to Pharma’ concept, space and space technology, energy climate change and environment are the areas that are mentioned as important in the country’s research and development strategy (DST, 2002).

The use of patent data to measure innovation has its drawbacks. One argument is that patents are not always representative of commercially exploited innovation, as it does not imply safe for use. However, the traditional role of patents is to provide inventors with an opportunity to recoup and profit from their inventions by providing them with a temporary monopoly to commercialise their research findings (Quach *et al*, 2006). It is therefore likely that inventors will patent those inventions they deem to have a better chance of commercialisation. Therefore, they may be more suited for use as representative of an input into the innovation rather than an output evidence of it, meaning that patents are just one of the inputs in the innovation value chain (Rogers, 1998). That being said, it is well established that patent data is still a useful proxy for measuring progress in innovations and has been used extensively for this purpose (Aspden, 1983; Abraham & Moitra, 2001; Luan & Zhang, 2011). Studies by Griliches (1990) suggested that there is a strong correlation between R&D expenditures and increased patenting activity. More importantly, a recent study looking at the BRICS countries by Kumar and Singh (2015) showed a direct relationship between number of patents granted and GDP of BRICS. The study led to the conclusion that increase in patenting activities amongst BRICS is a key factor for economic growth in these countries. Patent databases such as Patentscope from World Intellectual Property Organisation (WIPO), Spacenet for the European Patent Office (EPO) and the USPTO for the United States Patent and Trademark Office are used to extract the patent data (grants/registration) from which suitable indicators are derived. Other databases, such as the Derwent World Patents Index (DWPI), can also be used if the priority areas and countries under consideration receive sufficient coverage; this database is particularly useful for citation analysis.

WIPO’s Patentscope was used in this study. The advantage of this database is that it provides wide coverage of patents for South Africa and comparator countries of interest. It provides access to all International Patent Cooperation Treaty (PCT) applications in full text format on the day of publication, as well as to patent documents of participating national and regional patent offices, of which BRICS countries are part. The advantage of this database is that it allows for searching using keywords, names of applicants, IPC classes and sub-classes, as well as other search criteria. Since the aim is to search for patents by inventors from each of the countries in any jurisdiction across the globe, this was an ideal database for this purpose.

3.3.1 Some important issues on the use of patents for technology studies

Analysis of patents is done for various purposes from a legal and inventor purpose, including establishing prior art to determine the novelty of the patents. Proir art is an overriding concern particularly to patent examiners or even inventors. Otherwise, organisations may analyse patents for various reasons, such as determining patenting trends, forecasting technologies, in particular domain-identifying technology competitors and determining technological vacuums and hot spots (Abbas, Zhang and Khan, 2014). Various tools for doing this are available to extract the relevant patents from the various databases, including automated tools. The authors distinguish between text mining techniques and visualisation approaches. Abbas *et. al*. (2014) also notes that the most commonly used patent repositories are the USPTO, EPO and the Japan Patent Office (JPO).

While patent data does not provide a complete picture of innovation parttens in a field; a lot of information can be garnered from patents, for example the inventor, the office in which the patent is registered, the claims, the technological field(s) under which the patents fall, and, of course, the country of residence ofr the inventor(s). Based on this, we consider briefly how to retrieve patents for a specific field from a database, and important considerations for such a search. It is often said that the most natural way to search for any document is to use keywords. However, for patents, the use of keywords has its limitations, such as the fact that many companies use very unspecific vocabulary to make the scope of their patents as broad as possible (Eisinger *et al*, 2013). Based on these limitations, sometimes, for patents, the use of International Patent Classification (IPC) system, which is used in 189 countries, is beneficial.

The IPC divides technology into eight sections. In turn, each section is divided into classes, and classes further divided into subclasses, and subclasses into groups, resulting in approximately 70,000 subdivisions. Each subdivision has a symbol consisting of Arabic numerals and letters of the Latin alphabet (WIPO, 2015). The IPC system is particularly critical for the retrieval of patent documents in the search for "prior art." Prior art refers to any indication that the invention is already known, it does not necessarily have to exist physically or be commercially available. Patent-issuing authorities, potential inventors, research and development units need such retrieval, and others concerned with the application or development of technology. In this paper we use both the keyword and the IPC classification system for the search, depending on the technology area.

Some emerging multidisciplinary research areas that are of interest for human development, such as nanotechnology and climate change, have received social tagging, making it easier to search for patents relating to the technology area. The areas that have received social tagging are not usable for small countries like South Africa, as the EPO only does this for states that produce at least a certain minimum number of patents. This implies that South Africa does not really receive coverage by the patent offices simply because patenting is less than the minimum threshold. This may complicate the search for the patenting trends in these multidisciplinary areas of research that are of interest for human development.

Some of the indices that can be used in patent analysis are Technology Share (TS), Technology Leadership (TL), Technology Impact (TI), and Technology Market impact TM (Ernst; 2003, Geum, Lee, Yoon & Park; 2013). Another common indicator is the R&D efficiency, a ratio of patent output to the R&D expenditure, for example Thomas, Sharma & Jain (2011) used R&D efficiency ratio of patents granted to the R&D expenditure to compare the 50 states of the USA. The R&D efficiency is a very useful indicator, particularly for comparing performance of different entities, be it firms, countries or states within a country. However, in cases where the study involves different technology fields, a comparison of a number of patents across different technology fields may be misleading, as different disciplines have different patenting patterns. A useful indicator in such a case may be the revealed technology advantage (RTA), sometimes called a specialisation index. According to the OECD, the revealed technology advantage index provides an indication of the relative specialisation of a given country in selected technological domains and is based on patent application field. This indicator is related to the revealed comparative advantage index that measures specialisation in economics, as first described by Balassa (1965). It is defined as the country's share of patents in a particular technology field divided by the country's share of patents in all fields (see Equation 5). The RTA is zero when the country holds no patent in a given sector, is equal to 1 if the country's share in the sector equals the country's share in all fields (no specialisation), and above 1 when a positive specialisation is observed.

Equation 5. Revealed technological advantage

$$\text{RTA} = \frac{\text{The country's share of patents in a field}}{\text{The country's share of patents in all fields}}$$

Technological specialisation, as measured by RTA, is a useful tool comparison across different countries and different technological areas. This indicator has been applied and used for the comparison of different regions, countries and technological areas (Khramova, Meissner & Sagieva, 2013; Vertova, 1999). Technology specialisation shifts from country to country according to underlying technological competencies. Vertova (1999) points out that in the 18th century, when the railways technology was taking off, the UK was the world leader, whereas at the turn of the century, Germany, during the chemical industry, and in the information, communications and technology era, Japan seemed to be dominant. Additionally, RTA and patents share, both presented in this study, are the most useful of specialisation indicators in studies for the determination of the country's development stage, more so for when a comparison is made in different technology areas (Vertova, 1999).

National oriented policy makers make use of science and technology indicators based on patent data. However, it is particularly difficult to compare patents, as there are some shortcomings that were also identified in the OECD report (OECD, 1994), these include:

- A high presence of product patents compared to process patents

- Differing patent laws and procedure across regions
- Patents do not reflect any economic value
- Patent behaviours differ across industries, technology fields and sectors

The fact that there is a time lag between the application for a patent and the grant also presents another set of challenges. In the case of the EPO, a patent application is usually published within 18 months of application, whether it is granted or not, whereas in the USPTO before the year 2000 it was only published once granted, which could take up to five years. Most patent applications filed in the USPTO after the year 2000, are now also published 18 months after the filing date of the application. However, the use of patents has its own unique set of advantages, including the availability of patent data and very detailed information dating back several decades within the databases. In terms of technology development, the early stages of development are measured by publications and the patent being outputs from research and development and useful inputs of to the technology innovation. There are arguments that patent data is a direct measure of invention activity and is not really a direct measure of technological innovation or innovation activity. However, cumulative invention can be used as a proxy for technology innovation. The rate of growth can be used as a proxy for collective accumulative technological capability or socioeconomic competence.

3.3.2 Patenting in South Africa and other developing countries

Due to the fact that very little is known about innovative activities in the developing countries, in this study, an attempt to examine the inventive activities of a developing economy, in particular, South Africa, is done. Deorsola et al, (2017) on the review found that the BRICS have very differing intellectual property frameworks. The other BRICS, such as China, India and Brazil, have examining patent offices, although it takes quite a long time to get a patent granted in Brazil because of the low number of patent examiners in its National Institute of Industrial Property (INPI). Brazil and India, through Intellectual Property India, have a very well-established patent system dating back to 19th century in the case of India, which are also examining authorities. Russia modernised its intellectual property in 1996 and the patenting is managed through its Federal Service for Intellectual Property (Rospatent). Amongst the BRICS, China is the most active in the field of patenting in general. The Chinese patent office, called the State Intellectual Property Office (SIPO), issues the highest number of patents in the world with annual growth rates of more than 20% in patents for the last 15 years. Zhang (2010) attributed the growth of patenting in China to increased FDI, increased research spending and favourable legislation, such as the revision of Chinese patent law in 2000.

Further, most of the studies based on patent statistics have largely focused on developed countries, and less developed and developing countries have remained unrepresented. In a study of India and China patenting trends within the US system, interestingly, both countries are undergoing technology-based growth and tend to compete in many sectors. Both countries tend to patent their inventions in the US, as it is their main export market (Bhattacharya, 2004). This shows the dependence of developing countries on developed countries, not only in finding markets for their inventions but also as a source of knowledge. In a study in Brazil, using the data collected from the country's patenting authority, the INPI, it was found that most of the patent documents tend to cite knowledge produced in other countries, with the US representing more than 50% of such information (Pereira & Bazi, 2009). This highlights the relatively small base of infrastructure for scientific and technological production of researchers in developing countries.

In discussion of technology in general, there are various established facts supported by previous research in this field. Some of these, as mentioned by Sharma and Thomas (2008) are that technological change is a key factor for economic growth, technological improvement leads to an increase in total factor productivity, and sustains economic growth in the long run. In fact, the sustained economic growth in the developed economies can at least be partially attributed to their technological capabilities. R&D process is a major driver of technological change and various studies have confirmed this (Romer, 1990; Segerstrom, 1991). Facing competition brought about by globalisation, countries are striving to improve their technological capability. While many studies have been dedicated to understanding the technology diffusion and establishing the link between economy and the technological change, very little work has been done to understand the efficiency of the R&D process itself. Such studies are especially uncommon for a developing country like South Africa, as previous studies have concentrated on developed economies.

3.4 R&D EFFICIENCY

The R&D efficiency, a measure of productivity, is a measure of the number of outputs per unit inputs. Typically, the inputs comprise the research personnel and funding, and outputs are typically the publications and patents. However, it must be noted that during the R&D process it takes time to convert the inputs to output, the timeframe typically used is three years. For this reason, the R&D efficiency is calculated using the inputs from year one and outputs from year three. For example, in this case, the R&D efficiency at 2008 is calculated using the outputs (patents and publications) from 2008, and the R&D expenditure from 2006. This is shown by equation 6

Equation 6. R&D Expenditure

$$\text{R\&D Efficiency} = \frac{\text{Numberof patentsgranted}}{\text{R \& D Expinditue (US\$)}}$$

3.4.1 Analysing the R&D process

Evaluation of efficiency is very important if one wants to be competitive in an environment made severely competitive by globalisation. Efficiency in its basic form looks at the effect of inputs on outputs and can be analysed using different approaches through various tools. One of the most widely used tools for looking at performance efficiency is the non-parametric method called Data Envelopment Analysis (DEA) and can be used in a variety of settings, especially when one studies multiple inputs. A study by Sharma and Thomas (2008), which looked at the R&D efficiency of the 22 developed and developing economies using the DEA, found that amongst others Japan, South Korea, China and India are the most efficient and, as far as can be established, this list includes the developing and established economies. The authors concluded that this proves that efficiency is not exactly a function of the resources the country has at its disposal; in fact, the developing economies can serve as a benchmark on how the resources can be used effectively. It must be pointed out that South Africa was not included in this study as only countries with R & D expenditure above 0.75 percent of GDP were considered.

3.4.2 R&D Expenditure as an input

The input used was the gross domestic spending on R&D, and is defined as the total expenditure (current and capital) on R&D carried out by all resident companies, research institutes, university and government laboratories in a country (OECD, 2018). It includes R&D funded from abroad but excludes domestic funds for R&D performed outside the domestic economy. This indicator is measured in current PPP million US Dollars. The OECD describes the Purchasing power parities (PPP) as the rates of currency conversion (fictitious) that equalise the purchasing power of different currencies by eliminating the differences in price levels between countries. The BRICS countries comprise diverse economies with vastly different currencies and inflation rates, and therefore standardising the currency to the current PPP US dollar was deemed necessary. This approach has also become standard practice for such analysis used by other multilateral organisations, such as the OECD, the World Bank and the UNESCO. Expenditure on R&D as measured by the gross national R&D expenditure as a percentage of gross domestic product is widely regarded as a good indicator of a country's competitive potential (Blankley and Kahn, 2005).

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CHAPTER 4 SCIENTOMETRIC METHODOLOGIES

In this section, the methods used for the four parts of the scientometric study of the priority areas are presented and justified. This includes the scientometric study of priority areas, the patentometrics study, as well as the case study of the bibliometric study of nanotechnology development in the country. The first part (4.2) of the methodology looks at the bibliometrics study of four priority areas, the second section (4.3) of this chapter explains the methodology used for the patentometrics study, the third part (4.4) explains the methodology applied for the Nanoscience and Nanotechnology study, and finally, in section 4.5, the methodology for the R&D efficiency study is explained.

4.1 PHILOSOPHICAL PERSPECTIVES / RESEARCH DESIGN AND PHILOSOPHY

In this section, the available choice of appropriate methodology for this type of study was looked at. The choice of methodology is always determined by the research questions, and these have been presented in chapter 1. For this study, the methodological philosophy, the use of empirical data to make some inferences on the progress in the country priority areas in science and technology based on the research output were taken into conideration. The study did not focus on computing detailed statistics to prove causality or correlation; instead, the study addressed the research programme by use of widely used scientometric indicators and applied specifically to a new setting and context. Causal effect would be ideal if cause and effect can be proven between variables. However, this is often difficult when one analyses a science system where there are multiple factors and actors (see the models in chapter 3) that affect the outcome, some of which are not easy to measure. There is an admission that definite conclusions cannot be made with certainty. The data obtained is based on probabilities and therefore it is likely that in the discussion or conclusion, much of it starts with probably or most likely. It cannot be said or concluded, for example, that the country's policy on certain technology led to this outcome with certainty. The research therefore has a positivist interpretation approach to it in that it reflects a deterministic philosophy in which causes *probably* determine effects or outcomes (Mackenzie and Knipe, 2006).

The use of bibliometrics and patents data used for this study do not represent in totality, where applicable, the overall picture of R&D-led innovative activity in the country. However, they can be used to make inferences based on observation of data. The comparison with other countries is also meant to assist in this exercise so that analysis is not made in isolation. The descriptive approach used in this study complements the positivist research paradigm.

4.2 METHODOLOGY FOR THE BIBLIOMETRIC STUDY OF PRIORITY AREAS

In this study, the Web of Science (WoS) classification system was used, which is based on core journals classification. The research priority areas as well as WoS fields used for the classification of the publications are presented in Table 1. The table also refers to the applicable reference within South Africa where the field is classified as a priority.

Table 1. List of priority areas that are considered in this study.

Priority area	Web of knowledge classification	Reference Government Policy
Biotechnology	Biochemistry and Applied Microbiology	Biotechnology Strategy 2001
Energy	Energy & Fuels	RSA R&D Strategy 2002
Astronomy	Astronomy & Astrophysics	RSA R&D Strategy 2002
Palaeosciences	Palaeontology	Palaeosciences Strategy 2012

Data were collected on publications in these scientific research areas for fifteen years starting in 2001. The year 2001 is the year before the launch of the South African R&D Strategy. The SCI database offered by Clarivate Analytics (formerly Thomsons Reuters) WoS and InCites^{TM} were used exclusively for the search of journal publications to ensure consistency in comparison. The advantage of this database is that it provides a comprehensive coverage of the most important and influential journals and core literature internationally. According to the Thomson Reuters website, its collection covers nearly 25,000 international and regional journals, essays and book series in every area of the natural sciences, social sciences, arts and humanities. The advantage of InCite^{sTM} is that it enables the user to evaluate institutional or country productivity and benchmark output against peers worldwide.

In terms of energy publications listed under the 87 energy and fuels journals were used, Kajikawa, Yoshikawa, Takeda, and Matsushima (2008) followed a similar approach in their study. For astronomy, there is a relative consensus that the 60 publications in the Web of Knowledge listed under astronomy and astrophysics are representative of the core literature in this field. Bilir, Onal, Ozturkmen, and Yontan (2013) have followed this methodology in their study of research performance of Turkish astronomers. Palaeontology is one of the smallest research areas covered by WoS (Racki, 1997). However, while WoS does not provide coverage for the majority of journals, the most prestigious or the core ones are covered (Racki, 1997; Racki & Balinski, 1999). The 52 journals indexed under the Palaeontology WoS class are expected to be sufficiently representative of the core literature in this field, and these were used for the study. For the biotechnology publications, also, a simple methodology was followed by extracting publications under the biochemistry and applied microbiology classification; this method has been used by other authors (Martinez, Jaime & Camacho, 2014). According to Abramo *et al.* (2012), the appropriate duration of citation time should be at least three years to provide reliable citation data. Moreover, the study was limited to a period of up to 2015, otherwise the attractivity index would not have been reliable. In this study, only articles were considered, and other publication types such as book chapters and proceedings were excluded. Whole counting is used throughout this article, as explained earlier. Therefore, there is reasonable certainty that the results represent a realistic picture of all the research areas studied.

In this study, the research performance of South Africa was compared with BRIC countries and includes a comparison with Egypt, which is the second most productive country on the African continent after South Africa (Naravaez-Berthelemot, Russell, Arvanitis, Waast, & Gaillard, 2002; Pouris & Pouris, 2009; African innovation outlook, 2014). For comparison of the research areas between different countries, cumulative data between 2001 and 2015 are used, and for comparison of research areas within South Africa, data for the individual years from 2001 to 2015 are used. The comparison is made by computing the activity and attractivity indices for the selected fields in different countries, in addition to the usual indicators such as publication and citation counts.

4.3 METHODODOLOGY FOR PATENT STUDY

The relevant patents were extracted using either the keyword or the relevant patent class in cases where the technology area had clearly defined patent classes or subclasses. A patent is credited to a country if at least one of its authors is affiliated with an institution that has an address in that country. In the case of co-authored articles, each patent is credited to all countries that appear among the inventors' affiliations. A lot of work has been done to determine the difference in country rankings, arrived at using four different counting methods (i.e. whole counting, straight counting, whole-normalized counting, and complete-normalized counting) in patent counts. The issue with fractional counting is that it is time consuming and requires that the contents of the patents be studied in detail to assign the correct fractional count to each inventor. This may not be necessary as several studies show that counting methods have only minor (Zheng, Zhao, Zhang, Huang & Chen, 2014) to no effect (Elango & Rajendran, 2017) on country rankings in patent count. This does not mean the fractional count methodology does not have its proponents and is indeed a valid methodology for such studies (Huang, Lin, & Chen, 2011). It is important to note that there are other alternative search strategies that have been used in the past, such as forward searching, full text analysis and data mining (Couteau, 2014). Biotechnology patents, for example, can be extracted from several relevant classes as recommended in the OECD framework (OECD, 2005). Curran and Leker (2011) used a suggested method for the extraction of ICT patents from different patent classes and subclasses; this method was used for this study. In a case of nanotechnology, an attempt to use a new class that has been implemented was done. The implementation of the search was abandoned due to practical consideration of this class; keywords were used instead. For patents related to energy and health, the use of relevant keywords were made. The search terms or IPC class used are according to the table below. The table specifies the references of previous research that utilised similar methodology. The health patents are measured by using a combination of pharmaceuticals and medical device classes. Energy looked at all the classes that may encompass energy, including renewable energy and energy efficiency. A method adapted from Popp (2002) was used; this author used US patent classes and was converted to relevant IPC classes using the USPC-to-IPC Concordance tables. The patent search was carried out using the WIPO's Patentscope, as this is the most representative for all the countries considered in this study. In addition, the user interface is quite well-structured, allowing for the use of both keywords and IPC classes. Results can be further filtered by priority, date, applicant, and country, amongst others. It is worth noting that the classification of technology types has been an ongoing area of research and alternative methodology, such as the one suggested by Schmoch (2008).

Table 2 below shows the strategy followed for the extraction of relevant patents in the fields under consideration. The strategies followed for the individual technology areas are dependent on the unique structure of the technology. In several cases, methodology from the OECD working groups on science and technology were used. The OECD has a credible system and working groups consisting of experts from each of the participating member and observer countries in each area of technology. As a result, where such was available, a methodology from the OECD was used.

Table 2. List of priority areas that are considered in this study and the search strategy used to extract the patents.

Area	*Search strategy*	*Reference*
Nanotechnology	Codes Tag Y01N on EPO changed to B82Y class 977 on USPTO or Keywords	keywords as in Maghreb, Abbasi, Amiri, Monsefi & Harati, 2011
Biotechnology	IPC codes 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)	Chen & Guan, 2011 Arts, Appio & van Looy, 2013 OECD, 2005
ICT	IPC Codes H04M, G06C, G10 G03B, G01C	Curran & Leker, 2011
Energy	IPC codes see Addendum A2	Adapted from Popp, 2002
Health	IPC codes A61 [B, C, D, F, G, H, J, L, M, N], H05G. and A61K not A61K-008	OECD, 2009
Space & Satellite Technology	IPC codes & codes B64G AND a keyword search on these classes B64, C06, F41, F42, G01, G08, H01, H02, H03, H04, H05 Using the keywords satellite", spacecraft", "rocket", "space", "launcher"	OECD, 2011

An exploratory search was conducted, and the methodology was then optimised depending on what was obtained from that search. An exploratory search, for example, of nanotechnology using the special class B82 revealed very few patents. On close analysis, this class does not cover chemical or biological nanostructures, for example, provided for elsewhere, these would be expected to make a huge percentage of total nanotechnology patents. A use of keywords-based query, as described by Maghreb, Abbasi, Amiri, Monsefi and Harati (2011), revealed a more realistic picture on patent landscape. Similarly, an exploratory search under the relevant IPC class B64G (and some other classes, such as G01S19), which represents patents in the Cosmonautics, Vehicles or Equipment described as apparatus for, or methods of, winning materials from extra-terrestrial sources revealed less than 5 patents worldwide by South African inventors over the period under review. This shows the relatively low level of patenting for this technology within the country.

The reported patent counts are based on the priority date as per OECD recommendation, the inventor's address country, and one unit is allocated to all co-inventors mentioned in each patent (no fractional counting). A patent granted in different jurisdictions, called a patent family, is counted as one patent for an inventor. Data was downloaded from the WIPO's database PATENTSCOPE during the week of 22 -26 August 2016. The search was carried out using all patent offices where a patent with at least one South African resident as an inventor are registered. The methodology did not discriminate between the examining and non-examining jurisdiction.

4.4 METHODOLOGY FOR NANOTECHNOLOGY STUDY

Data was extracted on articles in nanoscience and nanotechnology for eleven years starting in 2005. The year 2005 is chosen because it coincides with the launch of the N&N Strategy in South Africa. It will not really add much value to go further back than 2005, as the previous study mentioned earlier (Pouris, 2007) covers this period up to 2005. The SCI database offered by WoS was used for the search of journal publications (Thomson Reuters, 2016). A major strength of this database is that it provides sufficient coverage of the most important and influential journals and core literature internationally. For the calculation of activity index and percentage share, the total for publications were obtained using InCites™, an analytical tool also provided by Clarivate Analytics (formerly Thomson Reuters) which uses the same underlying WoS data.

A keyword-based search is a preferred route for a relatively new and multidisciplinary field like N&N, as there are a high number of relevant publications that can be hidden in multidisciplinary journals. Based on this, a WoS core collection database was used, which allows the use of a keyword-based search. There are many search strategies used for nanotechnology from the simple use of the nano* wildcard, to a more elaborate approach such as a modular search strategy, as described by Porter, Youtie and Shapira (2008). A simplified methodology by Maghreb, Abbasi, Amiri, Monsefi & Harati (2011), that recognises that not all words that start with nano- refer to nanomaterials and that there are some nanomaterials that do not have keywords containing the nano- prefix such as quantum dots and fullerenes, was used. This methodology is used based on its simplicity and a very accurate recall of nanotechnology articles, and it consists of the following keywords: nano* NOT nano2 NOT nano3 NOT nanog* NOT nanosecond* NOT nanomol* NOT nanogram* NOT nanoplankton* OR "atom* scale" OR "atomic layer deposition*" OR "giant magnetoresist*" OR graphen* OR dendrimer* OR fulleren* OR "c-60" OR "langmuir blodgett*" OR mesopor* OR "molecul* assembl*" OR "molecul* wire*" OR "porous silicon*" OR "quantum dot*" OR "quantum well*" OR "quantum comput*" OR "quantum wire*" OR qubit* OR "self assembl*" or supramolecul* OR supermolecul* OR "ultrathin film*" OR "ultra thin film*". In this case, a top down keyword search and Boolean operators are used. This enables extraction of all articles that contain keywords known to be used in nanotechnology publications in case of the operator OR and for NOT the aim is to exclude those articles that may include the nano- prefix but are not related to nanotechnology. In this study, other publication types such as book chapters and proceedings were not included and only research articles were considered. In this study, we study the growth in N&N publications using the average annual growth rate (AAGR) which is an arithmetic mean of a series of growth rates. The formula for AAGR is represented as follows:

Equation 7. Average annual growth rate

$$AAGR = \frac{(\text{Growth Rate Period A} + \text{Growth Rate Period B} + \ldots \text{Growth Rate Period X})}{\text{Number of Periods}}$$

In this part of the study, a descriptive approach is used to identify the trends based on the publication data. The analysis focuses on countries with which South Africa collaborates the most on research, the most prolific research institutions in N&N research, the top journals selected by South African researchers, as well as the subject categories, since N&N is interdisciplinary.

4.5 METHODOLOGY FOR THE R&D EFFICIENCY STUDY

The data was obtained from publicly available sources; specifically, the details on R&D expenditures on nanotechnology and biotechnology were obtained from the R&D Survey (2017). The publications are extracted from the Web of Science provided by Clarivate Analytics (formally Thomson Reuters), while the patent data was obtained from WIPOs Patentscope database. The relevant patents and publications were extracted using either the keyword or the relevant web of science class, or patent class in cases where the technology has a clearly defined patent class. Biotechnology patents, for example, can be extracted from several relevant classes, as recommended in the OECD framework (OECD, 2005). Data was downloaded from the WIPO’s database PATENTSCOPE during the week of 7 -11 May 2018.

4.5.1 Extraction of patents, publications and R&D expenditure data

The table below shows the strategy followed for the extraction of relevant patents in the fields under consideration. The strategies followed for the two technology areas are dependent on the unique structure of the technology.

Table 3: The search strategy followed to extract the patents and publications for nanotechnology and biotechnology.

Area	*Search strategy*	*Reference*
Nanotechnology	Keywords for both patents and publications	Maghreb, Abbasi, Amiri, Monsefi & Harati, 2011
Biotechnology	IPC codes for patents 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	Chen & Guan, 2011 Arts, Appio & van Looy, 2013 OECD, 2005

The biotechnology publications are drawn from the Clarivate's Web of Science using the Biochemistry and Molecular Biology as a subject area. This is more representative of biotechnology core literature. Biotechnology is a more established field compared to nanotechnology and therefore the use of this subject area is conventional and has been used in past studies (Martinez, Jaime and Camacho, 2014; Makhoba & Pouris, 2016).

4.5.2 R&D expenditure data

The data on R&D expenditure was extracted from the OECD and the UNESCO data websites. The R&D South Africa R&D survey report contains the most recent data on the R&D expenditure within the country; this was used to supplement the data obtained from the OECD website. The R&D expenditure is expressed in purchase parity current United States dollars to enable comparison of expenditure in different years and different countries; this eliminates the effects of inflation and different exchange rates. The data thereby obtained and used for the calculation of the statistics is presented in Appendix C.

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CHAPTER 5 BIBLIOMETRIC ASSESSMENT OF SELECTED R&D PRIORITY AREAS IN SOUTH AFRICA, A COMPARISON TO OTHER BRICS COUNTRIES

This chapter addresses the first main research question regarding the production of research articles within selected R&D priority areas in South Africa. This is done by looking at the two specific research sub-questions being addressed, and whether the level of research outputs, as indicated by the number of journal articles, reflects the goals of the R&D Strategy with respect to the R&D priority areas, as well as the comparison with the comparator countries, which are the fellow BRICS countries, and Egypt. The results of the scientometric study are presented together with the use of suitable indicators, such as the number of publications, citations and world share, as well as the activity and the attractivity indices. The results lead to several observations and conclusions in this regard.

5.1 SOME SELECTED PRIMARY DATA REGARDING PUBLICATION TREND IN SOUTH AFRICA AND COMPARATOR COUNTRIES.

Table 4 presents some primary data on publication trends in South Africa and the comparator countries. It is clear that the BRICS countries differ quite widely in terms of the numbers.

1.1 Some primary data about South Africa and the selected countries

Some data about the publication trends in the six countries is presented in this section to gain an understanding of the scale of scientific activity.

Table 4. Number of publications in the selected fields in selected countries from 2001 - 2015

Country	Total Publications	Biotechnology	Palaeontology	Energy	Astronomy
China	1 814 800	40 674	2 334	40 235	18 337
India	553 753	16 433	546	8 835	10 893
Brazil	401 710	7 593	818	3 646	80 35
Russia	410 744	3 067	2 901	4 461	19 517
South Africa	111 002	2 121	471	1 210	3 526
Egypt	76 684	1 622	244	1 384	694

Table 4 shows that from the selected countries, China is the biggest contributor of scientific publications. The results show that among the BRICS countries, China is a leading producer of publications in the areas of biotechnology and energy. Russia is a leading producer of publications in astronomy and palaeontology, with China not far behind in both fields. It is interesting to note that Egypt is producing more publications than South Africa in energy research.

5.2 COMPARISON OF THE RESEARCH AREAS WITHIN SOUTH AFRICA

The chart below depicts the number of publications produced in the different areas from 2001 ending in 2015.

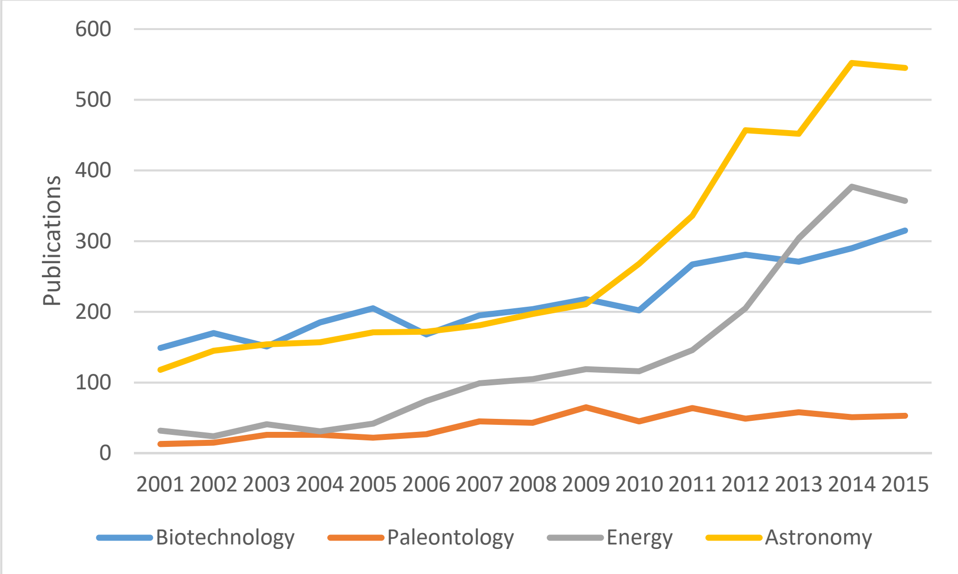

Figure 6. The number of publications in different research areas in South Africa

The results in figure 6 indicate that, in terms of publications, biotechnology and astronomy are experiencing a growth in terms of the number publications. The country's Biotechnology Strategy was launched in 2001 with accompanying government financial support a few years before this increase. The growth in publications in these areas can also be attributed to a general increase in publication in South Africa. Kahn (2011) found that the high publication rate in South Africa could be attributed to the fact that the Web of Science indexes more South African journals, and there has been an increase in co-publication with foreign authors. According to Pouris (2012) the other main reason was the growth in the new funding framework (NFF) for higher education institutions, which provides a cash incentive of more than R100 000 to the universities for each publication that their staff produces.

Table 5. The number of publications for different fields in South Africa from 2001 – 2015

Year	Country Totals	Biotechnology	Paleontology	Energy	Astronomy
2001	3 773	62	13	32	118
2002	4 060	68	15	24	145
2003	4 018	98	26	41	154
2004	4 371	75	26	31	157
2005	4 675	115	22	42	171
2006	5 358	127	27	74	172
2007	6 016	147	45	99	181
2008	6 805	158	43	105	197
2009	7 579	178	65	119	211
2010	8 247	183	45	116	268
2011	9 596	233	64	146	336
2012	10 154	136	49	205	457
2013	10 988	175	58	304	452
2014	12 293	210	51	377	552
2015	13 069	156	53	357	545

Table 5 shows the number of publications produced in each field per year since 2002. All the areas have grown since 2001, except for palaeontology in which the growth is not of much significance. Biotechnology, energy and palaeontology grew from a very low base, while the country already had a respectable output in astronomy in 2002. The overall number of publications increased from 3773 in 2001 to 13069 in 2015, a 246% growth. Looking at the focus areas, it is observed that palaeontology increased by 307%, while astronomy grew by 362%. The difference between these two areas is quite glaring and may point to the resources that the government has been dedicating to astronomy in an effort to attract the SKA project to South Africa. Looking at biotechnology, the growth was low at only 152% of the 15-year period, while the growth in energy was 1015%, admittedly from a low base of just 32 publications in 2002. Energy, especially renewable energy, is a key area of research as researchers attempt to find sustainable alternatives to fossil fuels that pollute the environment. Clearly, the growth in biotechnology is low and inconsistent with the level of funding that has been committed to it. However, it is important to note that this funding went to the biotechnology regional innovation centres with a mandate for commercialisation, it is therefore possible that research which produce publications may have been overlooked.

In the tables that follow, a comparison of different areas in South Africa is made using the activity indices and the attractivity indices that are tracked over a period. *The activity index was calculated from the statistics available from the citation report as obtained from WoS. The statistics used are % documents in the field divided by the % documents in the world for that particular field. As an example, for astronomy in South Africa, these values were 0.55 and 0.47 respectively over the period 2001-2015, giving an activity index of 1.17. In the case of attractivity, index % documents cited relative to subject area is divided by the % documents cited relative to the world.*

Table 6. Activity indices of the different fields in South Africa from 2001 – 2015

Year	Astronomy	Biotechnology	Energy	Palaeontology
2001	1,17	1,02	0,69	1,60
2002	1,51	1,02	0,38	1,67
2003	1,60	1,46	0,63	2,29
2004	1,49	1,03	0,49	1,92
2005	1,59	1,49	0,66	1,67
2006	1,49	1,36	0,94	1,72
2007	1,46	1,35	0,94	2,46
2008	1,36	1,29	0,85	2,14
2009	1,46	1,30	0,76	2,98
2010	1,65	1,15	0,70	2,52
2011	1,97	1,25	0,71	2,37
2012	2,54	0,78	0,81	1,90
2013	2,68	0,88	0,93	2,52
2014	2,83	0,95	0,96	2,08
2015	2,75	0,68	0,85	1,91

In terms of astronomy and palaeontology, South Africa is clearly producing significantly high output and seemingly produces roughly double the expected from its scientific size in these fields [Table 6]. In terms of energy, the output is less predictable than in 2001 where the activity index is 0.69; this went as high as 0.94 in 2007 and then down to 0.85 in 2015. The activity index for biotechnology is close to 1 for all the years under consideration, indicating that this subject emphasis in the country is equivalent to other areas.

Table 7. The citation counts for the different areas in South Africa from 2001 – 2015

Year	Totals	Biotechnology	Paleontology	Energy	Astronomy
2001	91 269	2 057	354	530	2 149
2002	92 977	2 481	401	250	4 085
2003	99 972	4 262	527	446	3 451
2004	123 364	2 108	588	501	4 341
2005	120 228	4 117	466	1 340	4 507
2006	126 778	2 803	422	1 264	7 831
2007	123 969	3 874	671	1 006	5 175
2008	133 297	2 821	461	1 713	9 239
2009	135 034	4 105	664	1 939	9 856
2010	147 533	4 297	692	2 140	8 022
2011	140 137	2 378	456	2 707	9 159
2012	144 266	1 958	297	1 478	14 939
2013	125 958	2 018	510	3 322	12 848
2014	120 282	1 682	370	2 970	21 961
2015	85 538	1 044	248	2 235	8 069

Table 7 shows the number of citations received by publications in the four areas under consideration in South Africa. Looking at this table, biotechnology and astronomy received higher citation counts compared to energy and palaeontology. However, this does not necessarily mean that biotechnology and astronomy are doing any better than energy and palaeontology, as different fields differ substantially in their publication patterns. This serves to illustrate the difficulty in comparing different research areas with different publication patterns and hence the use of the attractivity index.

Table 8. Attractivity indices of the different fields in South Africa from 2001 - 2015

Year	Astronomy	Biotechnology	Energy	Palaeontology
2001	0,97	0,23	0,92	2,53
2002	1,91	0,27	0,39	2,90
2003	1,43	0,35	0,61	3,25
2004	1,48	0,17	0,51	2,56
2005	1,65	0,32	1,24	2,28
2006	2,62	0,22	0,90	1,96
2007	1,87	0,28	0,58	2,84
2008	3,10	0,20	0,83	2,02
2009	3,13	0,26	0,79	2,94
2010	2,47	0,30	0,71	2,93
2011	2,94	0,19	0,74	2,11
2012	4,40	0,22	0,40	1,47
2013	4,67	0,24	0,82	2,96
2014	8,24	0,25	0,66	2,34
2015	4,26	0,23	0,68	2,21

Astronomy and palaeontology showed high attractivity index, and it can be deduced that South Africa produced roughly double the expected from its scientific size in these areas. The attractivity index for biotechnology is close to 1 for all the years under consideration, except for 2014 and 2015 [Table 8]. Abramo, D'Angelo, and Cicero (2012) recommends a period of at least three years for more realistic citation data, so the results for 2014 and 2015 are consistent with this recommendation indicating a time lag between a period when an article is published to when it gets cited.

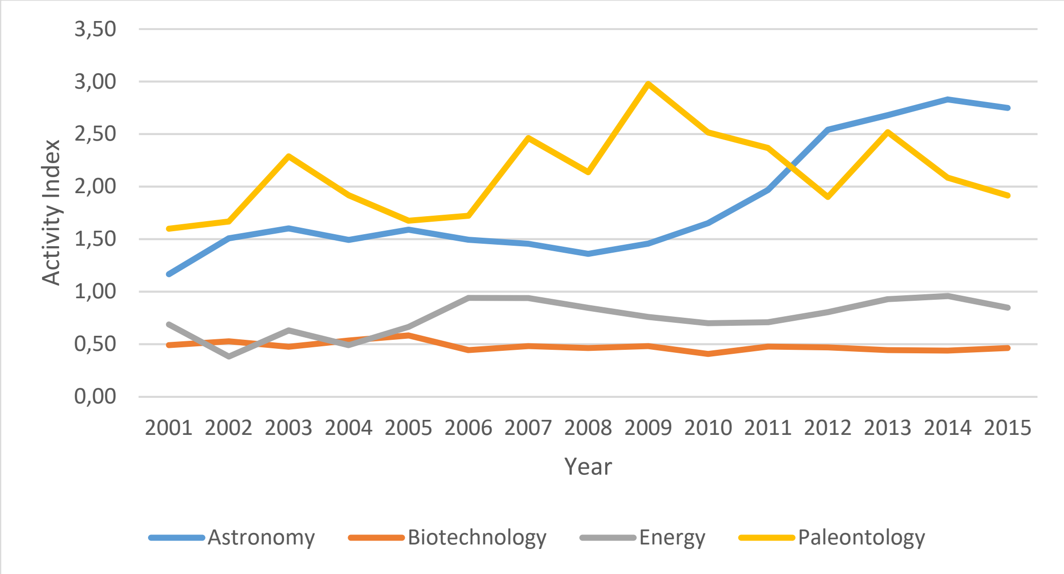

Figure 7. The activity indices of publications in priority research areas in South Africa from 2001 – 2015

The results in Figure 7 indicate that astronomy and palaeontology have high activity indices, indicating that South Africa produces roughly double the expected from the country's scientific size. This high activity index is mostly related to its geographical location; a high number of fossils have been found in the country, making it a focus for palaeontology-related research. In terms of astronomy, the clear night skies have made South Africa ideal for astronomy. South Africa developed the infrastructure to enable astronomy and space physics research, establishing facilities such as the Hartebeesthoek Radio Astronomy Observatory for radio astronomy and space geodesy, the Hermanus Magnetic Observatory for geomagnetism and space physics, as well as a facility in Antarctica (Martinez, 2008). Martinez (2008) further notes that due to these investments, the country has been able to attract big international projects in astronomy, such as the Square Kilometre Array (SKA). Energy has shown steady growth, getting close to the benchmark of 1 in 2014, and indicative that the efforts and resources dedicated to this field are yielding some results.

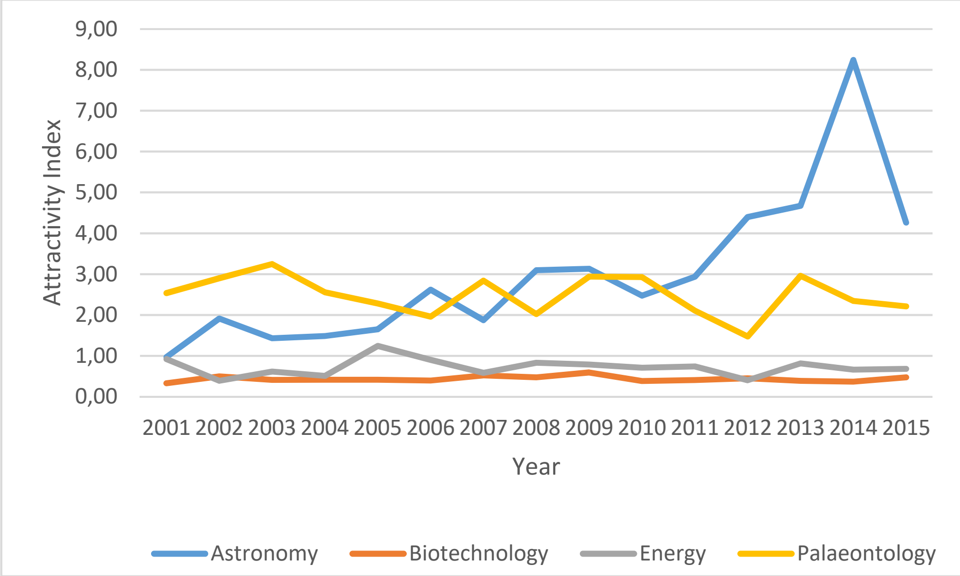

Figure 8. The attractivity indices of publications in different research areas in South Africa from 2001 - 2015

The results in figure 8 indicate that the attractivity indices of all fields display quite similar trends in terms of scientific impact and relative citations.

5.3 INSTITUTIONAL PROFILE OF THE RESEARCH OUTPUT IN SOUTH AFRICA

This section gives an overview of the institutional profile for the four selected research areas. It gives a representation of the institutions that published the most in the selected areas in South Africa during the selected period of consideration.

Table 9. Institutional profile of different areas in South Africa cumulative from 2002 -2012

Research Area	Web of Science Documents	Leading institution (no. of documents)
Astronomy	1 887	NRF(744)
Energy	629	UCT (99)
Biotechnology	2036	SUN(440)
Palaeontology	283	WITS (104)

According to the results presented in Table 9, the National Research Foundation (NRF), which manages the "National Facilities", accounted for 39% in the astronomy and astrophysics research output, followed closely by University of Cape Town (UCT) at 28%. The National Research Facilities under the NRF include the South African Astronomical Observatory (SAAO) and the Hartebeesthoek Radio Astronomy Observatory. The presence of the NRF as the most productive research institution in Astronomy can be directly accredited to the government investments in these facilities.

UCT accounted for 16% in the field of energy, closely followed by Stellenbosch University (SUN) at 12%. Both institutions have recognised energy as an important field of study and have established research centres in this field; namely the Energy Research Centre at UCT and the Centre for Renewable and Sustainable Energy Studies at Stellenbosch University. The Energy Research Centre at UCT is also responsible for publishing the Journal of Energy in Southern Africa, which is an ISI accredited journal.

Stellenbosch University is a leading organisation in biotechnology with a share of 22.0%, followed by the UCT that has a share of 13.4%. These organisations are ranked as leading universities in South Africa in terms of research output, so this is in line with the findings (Matthews, 2012).

Palaeontology is a relatively small field, with a few active researchers and few publications produced annually in comparison with the other research areas. Wits University produced 36.7% of all publications in palaeontology, followed by UCT at 17%. It is clear that Wits University placed a high priority in this area, as Bernard Price Institute for Paleontological Research and the Institute of Human Evolution are both based at this institution.

5.4 COMPARISON OF SOUTH AFRICA WITH OTHER COUNTRIES

In this section, the activity and attractivity indices of the different countries are given for the priority fields. The comparison of research outputs with other countries is made using the activity indices and the attractivity indices for the countries using cumulative data between 2001 and 2015.

Table 10. Activity indices of different areas in different countries cumulative from 2001-2015

Country	Biotechnology	Palaeontology	Energy	Astronomy
Mainland China	1,26	0.64	1.67	0.65
Brazil	1,67	0.87	0.81	1.17
India	1,07	0.46	1.52	1.20
Russia	0,42	3.44	1.04	2.89
South Africa	1,08	1.95	0.92	1.81
Egypt	1,19	1.65	1.02	0.45

The results in table 10 indicate that mainland China and India are paying particular attention to the biotechnology research area; this is also true for energy research. This is not surprising as biotechnology and energy feature prominently in China's 12th five-year plan. Russia and Egypt have low activity indices in the field of biotechnology indicating that these countries place less priority in these areas that may not be intentional necessarily. Russia, followed by South Africa, leads in the areas of palaeontology and astronomy, with India having the lowest activity index in palaeontology and China in astronomy. Basu and Lewison (2005) have highlighted the prominence of Russia in astronomy previously; therefore, this finding is not surprising.

Table 11. The citation counts for the selected areas in BRICS countries from 2001 – 2015

	Country Totals	Astronomy	Energy	Paleontology	Biotechnology
China	27 036 407	383 125	931 134	38 026	724 982
India	7 092 313	221 272	206 957	6 255	253 750
Brazil	5 254 998	188 008	71 983	9 743	123 045
Russia	3 995 593	397 942	28 966	18 625	47 593
South Africa	1 810 602	120 345	20 667	6 445	42 005
Egypt	913 864	17 288	21 060	2 497	22 595

Table 11 shows the number of citations received by publications in the four areas under consideration. The data is cumulative from 2001 to 2015. This serves to illustrate the difficulty in comparing different countries of different scientific size and hence the use of the attractivity index. Otherwise, the biggest country with a higher GERD and human capital will appear to be doing well at first glance.

Table 12. Attractivity indices of different areas in selected countries cumulative from 2001- 2015

	Biotechnology	Paleontology	Energy	Astronomy
China	1.19	1.01	2.45	0.69
India	1.58	0.66	2.08	1.51
Brazil	1.04	1.34	0.98	1.73
Russia	0.52	3.36	0.52	4.82
South Africa	1.03	2.56	0.81	3.22
Egypt	1.10	1.97	1.64	0.92

It is interesting that while there is a vast difference between the different countries in terms of publication output, the attractivity index reveals a very different scenario [Table 12]. The countries, on average, show an attractivity of close to 1 in the areas of palaeontology, energy and astronomy, meaning that the output, while varying, has comparable impact. All BRICS countries show attractivity index close to 1, showing that relative to citation in biotechnology is on same level with other field. While the activity index for Egypt and Russia is low in this field, the impact of the papers produced is of good quality.

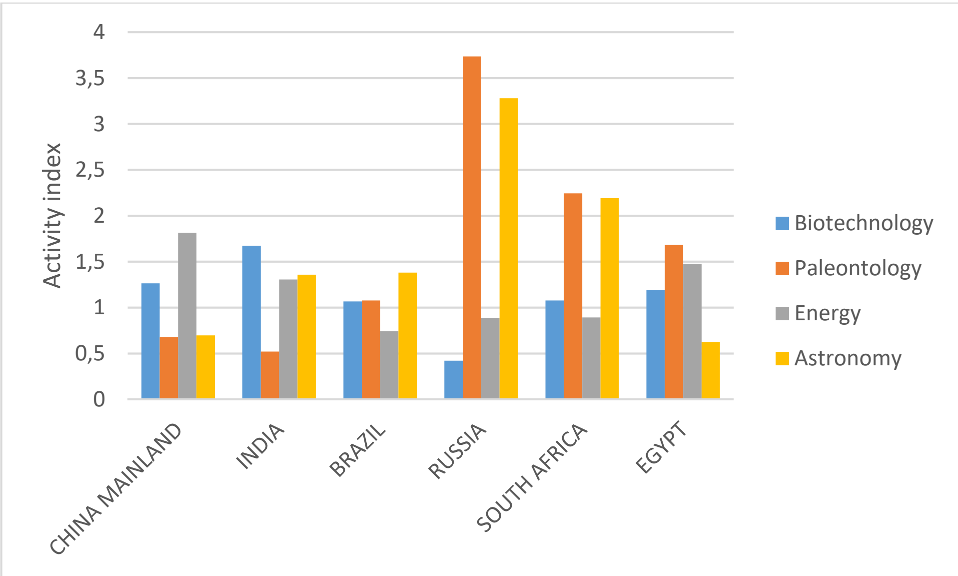

Figure 9. The activity indices of the research publications in different areas per country cumulative from 2001 - 2015

South Africa, despite its modest size, compares quite favourably with the other members of the BRIC grouping of countries of which it is now a member. It is clear from figure 9 that each of the countries has particular strengths. Russia, for example, places strong focus on astronomy and palaeontology. The emphasis on astronomy is most likely related to the country's historical development in this field. Interestingly, Mainland China has placed strong bias towards energy and biotechnology, which is not surprising as this country has a strong focus on these areas. China also gives high priority to both energy and biotechnology, as manifested by the number of programmes and government policies; they both feature explicitly in the country's 12th Five Year Plan. To further support this, the Chinese government established of the National Energy Commission (NEC), an inter-ministerial body responsible for overseeing energy development plans (Liping, 2011).

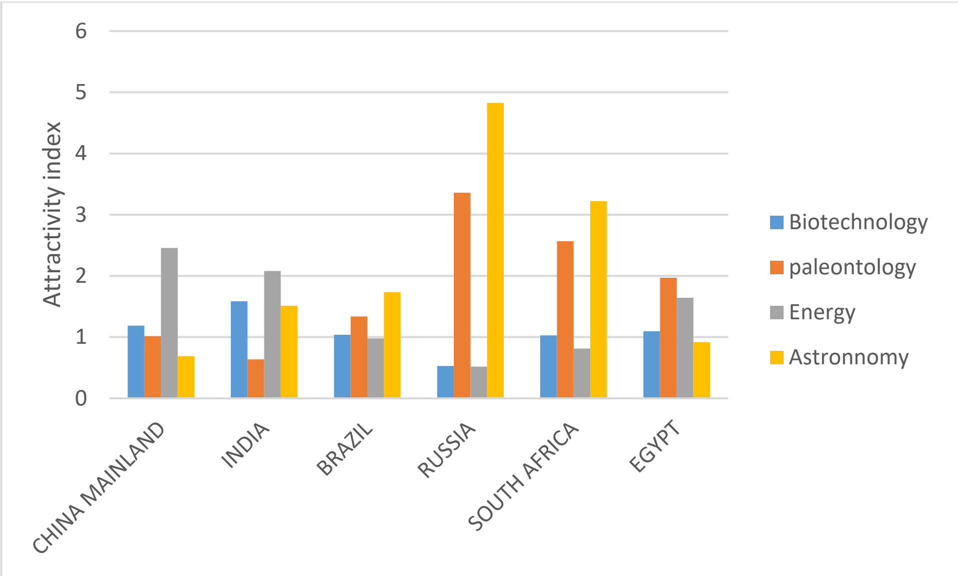

Figure 10. The attractivity indices of the research publications in different areas per country cumulative from 2001 to 2015

Figure 10 shows that in the areas of biotechnology, energy, palaeontology and astronomy, the attractivity index of South Africa is comparable to that of its peers in the BRICS group, demonstrating that the quality of publications based on citations in these areas is relatively good. However, South Africa, as newest member of the BRICS countries, needs to leverage its position and consider increasing collaboration with the other BRIC countries in biotechnology and energy research. Joint research programmes with a country like China, which has achieved a high level of output in these areas will be very beneficial. This collaboration with the BRIC countries should not be at the expense of the existing partnerships with other countries with which South Africa has already established programmes. A study by Finardi (2015) showed particular trends emerging in the collaborations between particular members of this grouping, showing strongest collaboration between South Africa and India. The authors attribute this to the fact that both countries belong to Commonwealth, were part of the British Empire and share English as one of the official languages. China and Russia also showed strong collaboration that was attributed to the presence of a Socialist State structure in both countries.

5.5 CONCLUSIONS

The study considered a selected number of research priority areas in South Africa. The research output of South Africa was compared to that of its peers in the BRICS grouping using relative measure of the attractivity index and the activity index. The findings of this study indicate that some priority areas have a relatively high output, while others are not. It can also be deduced from the publication data that certain institutions are emerging as leaders in these research areas in the country. Wits University is a leading institution in palaeontology, UCT in energy, Stellenbosch in biotechnology, while the NRF is a leader in the area of astronomy. When the progress between these areas is compared, it is clear that the investments in palaeontology and astronomy are showing results, although the rate of growth in palaeontology is an area of concern. This is very interesting, as both these fields relate to South Africa's geographical advantage. Therefore, South Africa has been able to exploit its geographical advantage using several policy instruments and funding, particularly in the build up to the SKA bid. Publication outputs in energy and biotechnology are in line with the country's scientific output in other areas, and the trend is in line with the overall growth of publication output. It is noted though that the growth in biotechnology lags far behind the overall growth of publications. Clearly, the DST identified that not everything was going well in biotechnology, hence the introduction of a new strategy, the Bioeconomy Strategy (2013); this will most likely help channel resources for research to the right institutions. What is positive about all of this is that despite varying levels of outputs across the different fields, the work from South Africa is highly regarded, as shown by the level of citations it attracts. Despite limited resources, the country's output in terms of publications are comparable to that of its peers in the BRICS group of countries.

In a comparison of the OECD countries, it has been found that in 2012 the gross expenditure on R&D as a percentage of GDP was 0.75% for South Africa, whereas the average for OECD countries is 2.39%; interestingly for China this value stood at 1.98% for 2012 (OECD, 2014). This, therefore, shows that South Africa is lagging in terms of R&D expenditure relative to other countries. This may prove to be a challenge in future in terms of maintaining the level of output as demonstrated in this study. In future, it will be interesting to consider other priority areas, such as nanotechnology, information and communications technology, as well as global climate change research, for a complete view of the country's performance in its chosen priority areas. Collaboration among the BRICS countries is an area that will also need to be considered in future, since these countries have been developing structures to ensure closer cooperation in science.

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CHAPTER 6 A PATENTOMETRIC ASSESSMENT OF SELECTED R&D PRIORITY AREAS IN SOUTH AFRICA, A COMPARISON WITH OTHER BRICS COUNTRIES

This chapter addresses the second main research question regarding the patenting activity within R&D priority areas in South Africa as the focus of this study. The two specific research sub-questions being addressed are whether the level of patenting reflects the goals of the R&D Strategy with respect to the R&D priority areas, as well as the comparison with the comparator countries, which are the fellow BRICS countries, and Egypt. The results lead to several observations and conclusions in this regard.

The reported patent counts are based on the priority date as per OECD recommendation, the inventor's address country, and one unit is allocated to all co-inventors mentioned in each patent (no fractional counting). A patent granted in different jurisdictions is counted as one patent for each country. Data was downloaded from the WIPO's database PATENTSCOPE during the week of 22 -26 August 2016.

In this study, data on patents for South Africa in each of the technical areas was extracted from the database. The data on patent numbers produced worldwide in each of the areas was also extracted to calculate the world share in each of the fields. The next step was to extract the data on patents produced by the different regions over the period of study, also to calculate their share over this period. The percentage share data thus generated was used for the eventual calculation of the RTA.

6.1 SOUTH AFRICA PATENTING PROFILE

Table 13 shows the top three leading organisations in South Africa in terms of patent output in the different focus areas.

Table 13. The top three patenting organisations in each of the sectors in South Africa

Nanotechnology		**Health**		**ICT**		**Energy**		**Biotechnology**	
Total patents	**105**	**Total patents**	**269**	**Total patents**	**112**	**Total patents**	**580**	**Total patents**	**194**
Patenting Organisation	**Number of patents**	**Patenting Organisation**	**Number of patents**	**Patenting Organisation**	**Number of patents**	**Patenting Organisation**	**Number of patents**	**Patenting Organisation**	**Number of patents**
Element Six (South Africa)	25	University of the Witwatersrand (South Africa)	38	Kahn, Ari (South Africa)	11	Sasol Technology (South Africa)	91	University of Cape Town (South Africa)	21
CSIR (South Africa)	8	University of Cape Town (South Africa)	18	Telkom (South Africa)	3	Element Six (South Africa)	9	CSIR (South Africa)	19
PST Sensors (South Africa)	7	North West University (South Africa)	11	U-MAN Universal Media Access Networks	3	PetroSA (South Africa)	8	Stellenbosch University (South Africa)	15

It was found that energy at 580 patents, is an area of research with the highest number of patents, followed by health at 269 patents, then biotechnology and ICT, while nanotechnology showed the lowest number of patents at 105 in various patenting offices worldwide. South African inventors produced a total of 105 patents in nanotechnology with Element Six, the synthetic diamond producer described earlier, producing the highest. Interestingly, PST Sensors, is a company founded by a professor from the University of Cape Town (UCT).

The areas of health are also dominated by the universities, with the University of Witwatersrand producing 38 patents out of a total of 269 patents. The university hosts the Wits Health Consortium (Pty) Limited, a wholly owned company that pursues entrepreneurial innovation in health and supports clinical trials. This university therefore is focusing on taking its research outputs beyond the laboratory. There is some participation of the multinationals in this field, with companies like Bayer Healthcare, Adcock Ingrams and Unilever having some patents in this area; these are in low quantities.

In the case of ICT, a leading inventor is, in fact, an individual by the name Ari Kahn. This individual at some point collaborated with the Mobile Telephone Networks (MTN), as one of the patents is owned by the MTN. MTN is a South African mobile telephone service provider. Telkom and UMAN, a German software company, each own three patents in this area. Telkom is a partially state-owned telephone company that provides mobile and fixed line telephone networks. There is lower presence of universities and science councils in this sector with patents mostly granted to individuals and start-up companies.

The country produced a total of 580 patents in energy [Table 13]. In the area of energy, Sasol Technology produced a total of 91 patents, making it the highest producer of patents in this area. Sasol Technology is a research and development subsidiary of the Sasol limited, a Johannesburg and New York Stock Exchange listed petrochemicals company, famous for producing oil from coal through the company's proprietary Fischer-Tropsch process. This is followed by Element Six, a synthetic diamond and related technology company and a part of the De Beers group - one of the world's biggest diamond producers. The synthetic diamonds and related materials are used for many industrial applications across a range of industries. In third place is PetroSA, which is the state-owned petroleum company that mostly produces fuel and petrochemicals from natural gas. These were the only sectors found to be dominated by commercial companies in terms of patenting.

Biotechnology patenting is dominated by the universities and the government owned science councils, with the UCT producing the most patents in this field, producing 21 out of the total of 194 patents produced by inventors in this country. The university is consistently ranked among the top in terms of research output and this explains its leadership in biotechnology. The Council for Scientific and Industrial Research (CSIR) is active in both nanotechnology and biotechnology.

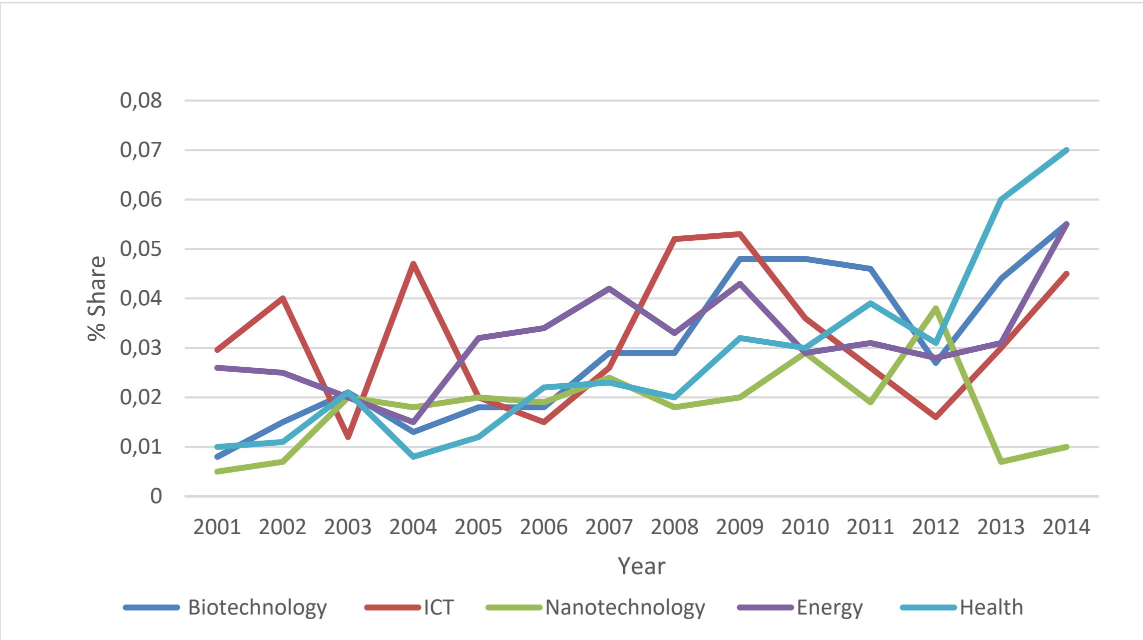

Figure 11. The South Africa's percentage share of patents in different areas from 2001 – 2014

Figure 11 shows the percentage share of each of the priority areas compared to the total patents produced by inventors in the country. There is no clear trend, which demonstrate the lack of consistency within the areas examined in South Africa. In nanotechnology, patents share, for example, was less than 0.01% in 2001, and in 2013 it was still less than 0.01%. One notable exception is the patent share of health-related patents that increased from 0.01% in 2001 to on 0.07% in 2014.

Table 14. The world share percentage of patents in different technologies for South Africa

Year	Biotechnology	ICT	Nanotechnology	Energy	Health
2001	0.008	0.029	0.005	0.026	0.010
2002	0.015	0.040	0.007	0.025	0.011
2003	0.021	0.012	0.020	0.020	0.021
2004	0.013	0.047	0.018	0.015	0.008
2005	0.018	0.020	0.020	0.032	0.012
2006	0.018	0.015	0.019	0.034	0.022
2007	0.029	0.026	0.024	0.042	0.023
2008	0.029	0.052	0.018	0.033	0.020
2009	0.048	0.053	0.020	0.043	0.032
2010	0.048	0.036	0.029	0.029	0.030
2011	0.046	0.026	0.019	0.031	0.039
2012	0.027	0.016	0.038	0.028	0.031
2013	0.044	0.030	0.007	0.031	0.060
2014	0.055	0.045	0.010	0.055	0.070
2015	0.969	0.257	0.056	0.289	0.501
2005-2015	0.029	0.032	0.018	0.032	0.023

Table 14 shows the world share of patents in total for South Africa in each of the priority areas during the 2001 to 2015 period by various patenting offices. It is observed that in the areas of energy, ICT and biotechnology have a world share of 0.03%, and nanotechnology and health have almost the same world share at 0.02%. It is clear that the latter two areas have been increasing their share, unlike ICT and biotechnology.

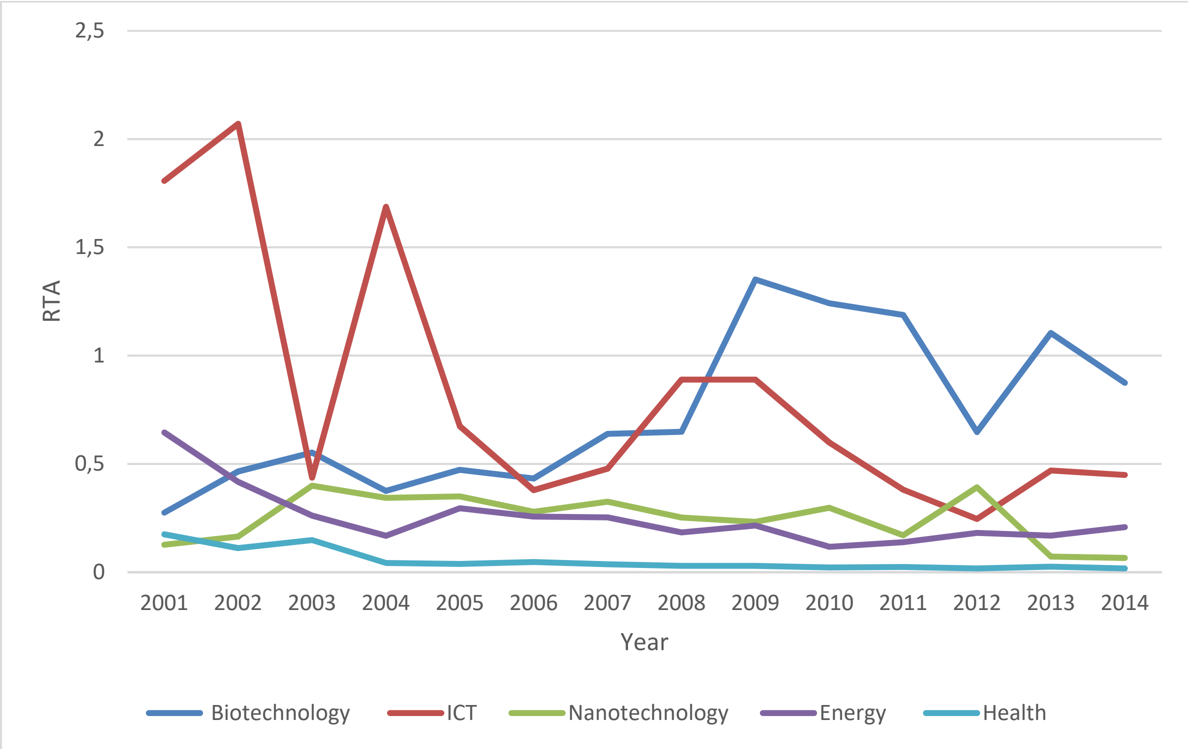

Figure 12. The specialisation indices for the research areas in South Africa from 2001 – 2014

Figure 12 shows the revealed technological advantage of each of the priority areas within South Africa.

The RTA was calculated from the statistics available from the patent data as obtained from Patentscope. Explicitly, the percentage patents in the particular technology area is divided by the percentage patents in the world for that particular field, the data is available in the annexure. It is observed that in all areas except biotechnology for 2011 and 2013, as well as ICT in 2001 and 2004, the values were significantly less than one indicating that the country has no technological advantage in each of these fields. Health, when compared based on the RTA in general, seems to be much worse off than all the fields studied. Figure 13 indicates that the specialisation indices of all fields display quite similar trends, with biotechnology showing a marked increase from a low base in 2001. Conversely, the index for the ICT area has been decreasing steadily from above 2 in 2002 to less than 0.5 in 2015. Nanotechnology, energy and, in particular, health research is not doing well at all over this period as the index has been consistently low for the whole period under review.

6.2 COMPARATIVE ANALYSIS WITH THE BRICS COUNTRIES

Table 15 details the percentage world share of patents for South Africa and each of the comparator countries.

Table 15. The world share percentage of overall patents for the BRICS countries

Year	South Africa	Brazil	Russia	India	China	Egypt
2001	0.032	0.016	0.043	0.040	0.062	0.0003
2002	0.033	0.019	0.044	0.059	0.099	0.0015
2003	0.038	0.026	0.049	0.078	0.141	0.0024
2004	0.035	0.028	0.053	0.087	0.187	0.0023
2005	0.038	0.030	0.057	0.111	0.314	0.0037
2006	0.042	0.039	0.070	0.134	0.473	0.0025
2007	0.045	0.054	0.075	0.165	0.624	0.0037
2008	0.045	0.059	0.073	0.178	0.694	0.0039
2009	0.035	0.059	0.086	0.199	1.073	0.0051
2010	0.038	0.060	0.097	0.246	1.390	0.0042
2011	0.039	0.069	0.109	0.224	1.645	0.0040
2012	0.042	0.066	0.097	0.158	1.805	0.0041
2013	0.040	0.064	0.096	0.181	2.349	0.0047
2014	0.063	0.100	0.147	0.267	4.138	0.0072
2015	0.056	0.092	0.077	0.299	4.523	0.0029
2005- 2015	0.039	0.045	0.073	0.1397	0.869	0.0032

In terms of patents found on WIPO for each of the priority areas in the BRICS countries, results reveal that, as expected, China followed by India produce most patents, with South Africa producing the least within this grouping of countries. It is important to note the magnitude of the Chinese output as they produce more patents than all the other BRICS member countries combined, in all the areas being investigated.

Data was extracted on the total number of patents granted in each of the areas, to inventors in each of the BRICS countries during the 2001 to 2015 period, by various patenting offices. The results presented, according to the priority date, once again show that China, followed by India, produce most patents, with South Africa producing the least. In addition, China and India are growing their patenting activity quite aggressively as opposed to South Africa that has not grown the number of patents much during the period.China, specifically, has been intensifying its efforts in patenting, increasing is share from 0.06% in 2001 to 4%.

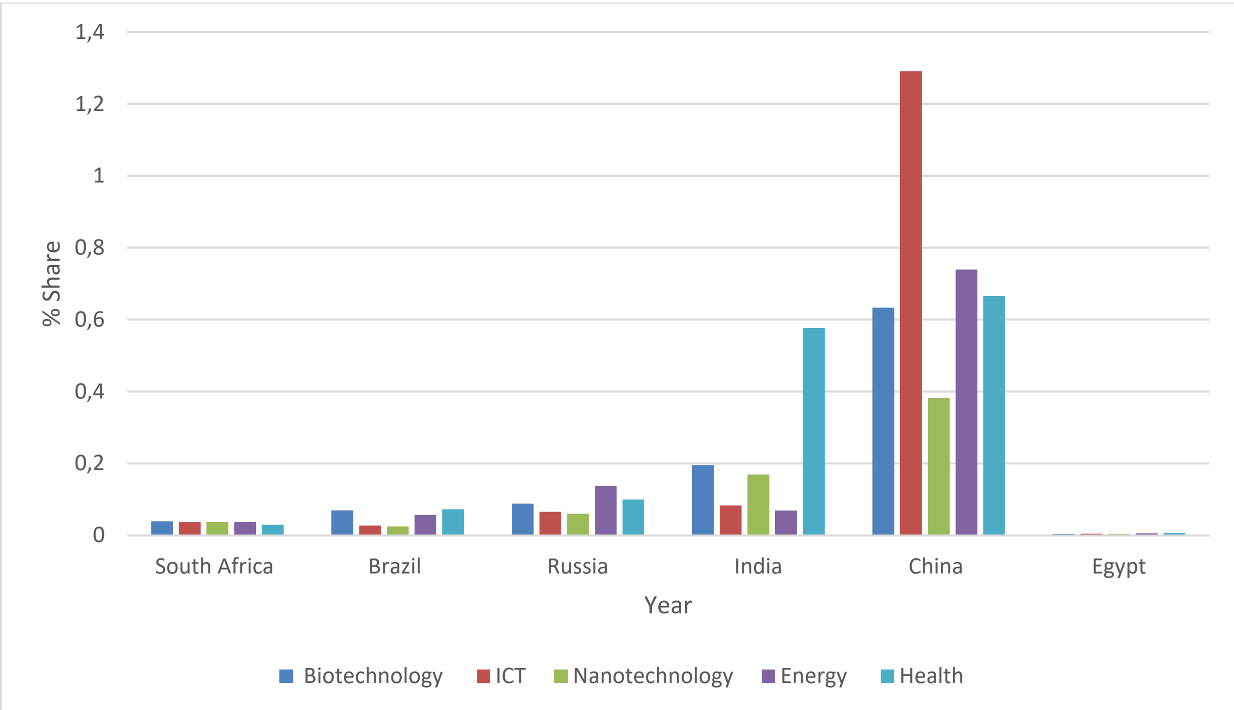

Figure 13. Patents percentage share in different areas per country cumulative from 2001-2015

Figure 13 shows the percentage share of patents in each field in each of the priority areas for South Africa and the comparator countries. It further demonstrates wide differences between the sizes of the innovation systems within the BRICS countries. In this case of patents share, China is a leading country, followed by India, with the two African countries having very little share of patents when compared to the worldwide production in this field. The share of South African patents for most areas is around 0.03% and, notably, South Africa has a higher share in nanotechnology than Brazil and Egypt.

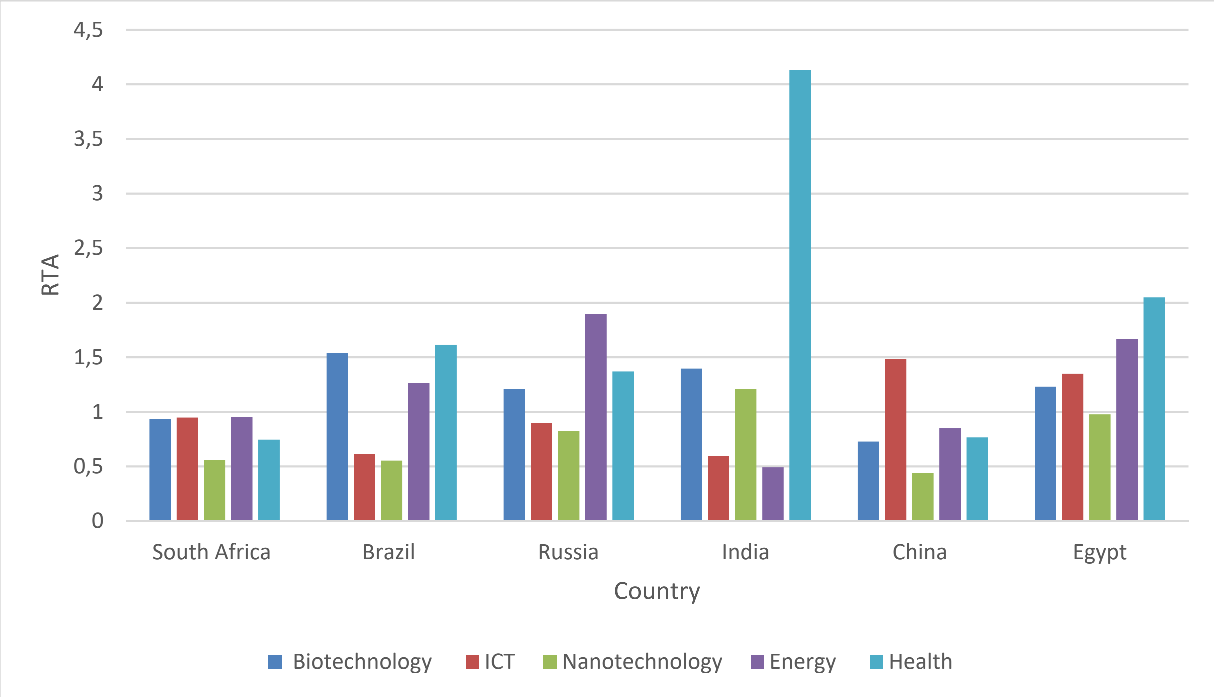

Figure 14. The specialisation indices in different areas per country cumulative from 2001 – 2015

Revealed technological advantage for South Africa and each of the comparator countries is shown in the figure that follows (figure 14). The results show that while China tends to have a large share of patents worldwide, the country's revealed technology advantage is much lower than those of other countries. India showed a big emphasis in the area of health, with only the ICT and energy showing the value of less than 1, so there is specialisation in the areas of biotechnology, nanotechnology and health. While Egypt files relatively few patents each year, the areas examined show that the country specialises the area of health with an RTA of above 2, while ICT and biotechnology just above 1. On the contrary, South Africa has a larger share of patents, but the emphasis and prioritisation is not in any of the fields studied, with all the values at less than 1, indicating no specialisation.

Figure 14 indicates that the specialisation indices of all fields display quite similar trends with India, and to a lesser extent, Egypt, showing a marked specialisation in the areas of health over the period under review. Therefore, in terms of the RTA, the performance of South Africa is comparable to that of the other BRICS countries. In addition, the two African countries considered in this study showed extremely low percentage share of output in all fields studied. The fact that the RTA is lower than 1 in all these priority areas shows that there is no higher emphasis of these technology application areas compared to general patent output in the country.

6.3 DISCUSSION AND IMPLICATIONS

Looking at the patenting trend within the priority areas, it is clear certain things are not working as expected. The level of patenting is very low. Countries like South Africa and Egypt certainly have decent level of patent outputs in these fields, but this does not extend to patenting. The issue of patenting is problematic in the African continent with the lack of regional integration being a possible obstacle for inventors. The patenting systems regionally do not offer a one-stop shop as in other regions, leading to territorial patent laws (Sayagues, 2015). This leads to very low level of patenting. For example, of the 2.5 million patents filed in 2013, only 0.6% were from African inventors. Clearly, there needs to be more integration, and processes need to be seamless between the patent offices.

There are some public policy implications that emerge because of the findings, particularly for developing countries. It is clear that the South African inventors have not increased their patents substantially despite the introduction of the National Intellectual Property

Management Office (NIPMO) and the enactment of the Intellectual Property Rights from Publicly Financed Research and Development Act (2008) - it seems that very little has improved. The aim is to protect intellectual property and intellectual property rights that are created with public funds. Few policy interventions, such as a stringent patent office, will legitimise the CIPC, and inventors are likely to approach it to register their inventions. Funding instruments can also emphasise patenting, in addition to publishing – that, for example, the Chinese government currently incentivises.

Interestingly, towards the end of the year 2017, South Africa's Department of Trade and Industry released the Draft Intellectual Property Policy of the Republic of South Africa. This draft policy has several proposals in terms of changing the existing intellectual property regime. These, amongst others, include the introduction of substantive search and examination for patents, a critical improvement, as it means all patents will be examined for their validity before registration, stimulating genuine innovation. The leveraging of flexibilities contained in the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) to ensure that South Africa protects IP rights while simultaneously promoting public health, local manufacture, research and development, innovation, food security, environmental considerations, transfer of technology and broad socio-economic development. Other proposals are the creation of a system for protection of traditional knowledge that will safeguard misappropriation and exploitation, as well as promote further research and development into products and services based on traditional knowledge. These changes mark a major change in the approach of IP management and, once implemented, are bound to have a positive effect in future.

6.4 CONCLUSIONS

The study considered patenting activity in a selected number of research priority areas of South Africa. The research output of South Africa is compared to that of its peers in the

BRICS grouping, using relative indicator, relative technological advantage, or specialisation index. Findings of this study indicate that the government prioritisation of these areas has not translated to increased patenting activity in these areas and a lack of specialisation. Therefore, while the overall patenting trend in South Africa is positive this is not affecting the priority areas. The comparison with the other BRICS countries demonstrate that China and India are quite dominant in patenting, based mostly on the differing sizes, but clearly there are some areas of research that these countries have prioritised, with health receiving a higher priority in India, for example.

South Africa has a relatively low patenting culture as evidence from results shows. There needs to be a focus on incentivising international patenting to move research from the lab towards the market as is the objectives of the government policies. According to the last available figures, which are from the 2013/14 period, the GERD as a percentage of GDP for South Africa stood at 0.75%, the BERD is 0.32%; this low investment in general by the business in researc, and development could be an explanation for the low level of patenting. To put this into perspective, the average GERD as a percentage of GDP, and BERD as a percentage of GDP, for the OECD countries is 2.38% and 1.58% respectively.

The South African patent office, known as the Companies and Intellectual Property Commission, needs to be transformed and patents applications must go through the examination to assess their substantive validity. An examination process is a proven method to ensure quality submissions go through the system and should be put in place with urgency accompanied by appropriate legislation. It is established that stronger patent protection leads to a higher tendency of industry to invest in innovation (Allred & Park, 2007). Therefore, relevant legislation in line with international best practice will encourage private sector to increase patenting activity. The government policy and funding for research alone may not be the most appropriate mechanism due to its indirect connection to technological innovation. It is the market pull that is likely to drive patenting; this and the capacity to deliver the product to the market, which is most efficiently done by private enterprise.

6.5 REFERENCES

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CHAPTER 7 THE DEVELOPMENT OF NANOSCIENCE AND NANOTECHNOLOGY RESEARCH IN SOUTH AFRICA: ANALYSIS THROUGH BIBLIOMETRICS

The aim of this study was to investigate the productivity and intellectual structure of N&N in South Africa since the launch of the country's N&N strategy. In this section, the results of the bibliometric study obtained from the analysis of the 2928 records extracted from the ISI indexing database, and published in the eleven-year period between 2005 and 2015 are presented.

The first part considers the publication and citation trend, the second part the collaboration and the most productive countries and institutions, and finally at the intellectual structure of the nanotechnology research. A search on the patents, using the same keywords as used for publications, revealed that South Africa has been granted less than 10 nanotechnology patents by the USPTO over this period and, as a result, patents did not form part of the study. This was confirmed using the OECD database (OECD, 2016), and based on the available data, further analysis was abandoned as it will not add further insight to this study.

7.1 THE NANOTECHNOLOGY PUBLICATION TREND IN SOUTH AFRICA

Figure 15 shows the publication trend of nanotechnology articles in South Africa from the year 2005 to 2015.

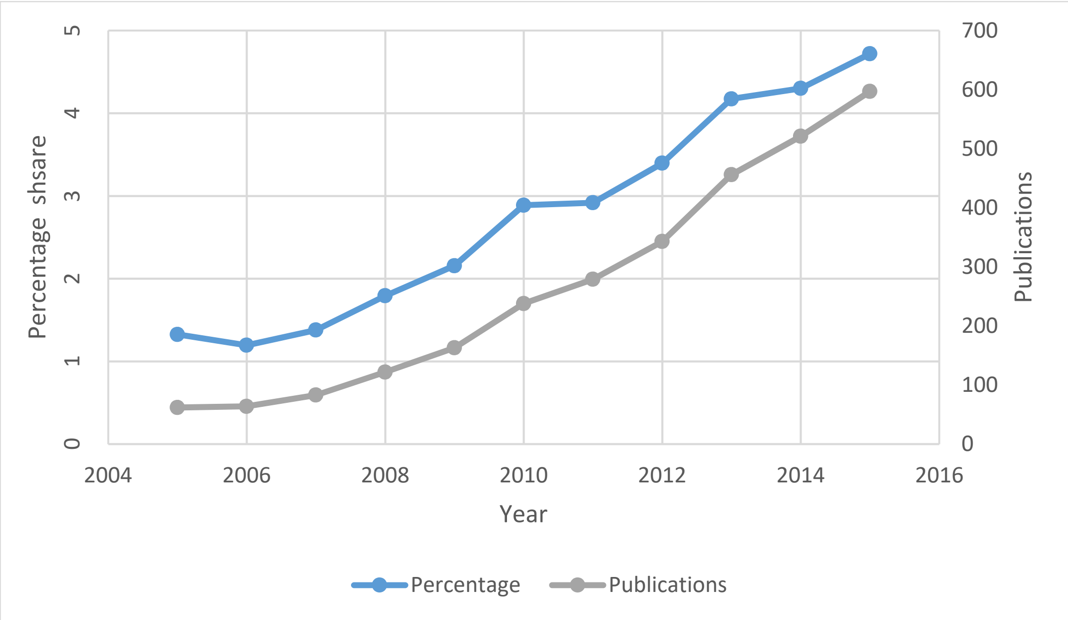

Figure 15. Graphs showing the publication trend as well as percentage of N&N articles relative to the total number of articles in South Africa from 2005 to 2015

Figure 15 shows an increasing trend starting in 2005 where only 62 publications were produced in this country; this has grown steadily to a total of 597 in the year 2015. This represents an average annual growth rate of 22%. The publications have grown substantially for the N&N area but, to put this in context, the overall publication numbers in South Africa grew from 6408 in 2005 to 15468 in 2015 equating to an average annual growth rate of 14%, so N&N is growing at a much faster rate than the general growth of publications in South Africa, which equates to an average annual growth rate of 0.36%. Regardless, this growth in the N&N represents almost tenfold growth in output over the period demonstrating that this area has been seeing a lot of growth in terms of publications.

To ascertain if the significance of the growth in nanotechnology articles, a percentage of nanotechnology articles to overall articles from the country during the period was calculated. It is clear from Figure 1 that this grew from less than 1.5 in 2005 to just above 4.5 in 2015 a threefold growth. So, indeed, the N&N publication growth trend is much higher than the overall growth of articles over time generally, and the proportion of N&N articles is increasing in real terms over time. This growth is distinct, for example, to that of energy publications, which has remained stagnant since 2008 according to a recent study (Pouris, 2016).

7.2 THE CITATION TREND OF NANOTECHNOLOGY PUBLICATIONS IN SOUTH AFRICA

Figure 16 shows the citation trend of nanotechnology articles in South Africa from the year 2005 to 2015.

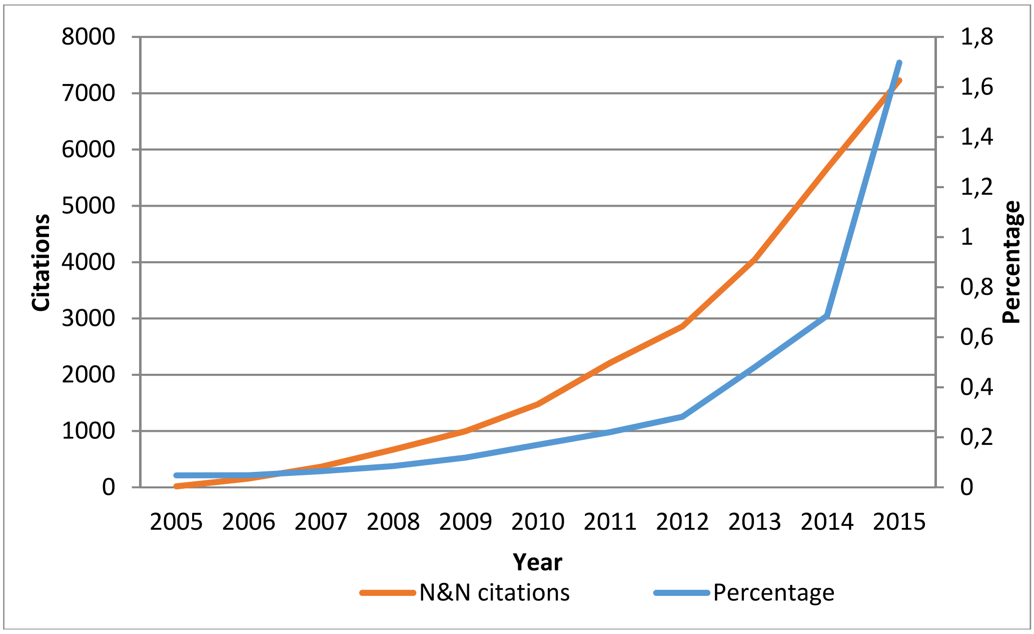

Figure 16. Graphs showing the citation trend as well as percentage of citation of N&N articles relative to the total number of citations in South Africa from 2005 to 2015

An observation of the citations of the articles reveals an even more impressive picture (Figure 16). The citations have grown from 18 citations to 7229. This represents an average annual growth rate of 72%, which is quite impressive considering that the overall growth in citations in the country was quite low. Citations for South African publications, as such, have not grown much with a growth of 1.81% between 2005 and 2010 compared to 251% for N&N over the same period. This shows that the nanotechnology articles generated by South African researchers have relatively high visibility.

In the case of citations, to determine the significance of the growth in citations in nanotechnology articles, a percentage of citation of N&N articles to total citation of articles in South Africa was calculated. As seen from the secondary axis in figure 2, this grew from just 0.04 in 2005 to above 1.6 in 2015, a real growth. This, therefore, shows that the growth trend in citation of nanotechnology articles is by far much higher that the growth of citation of other South African publications over time generally.

Table 16 shows the publication and the citation trend of nanotechnology articles in South Africa from the year 2005 to 2015. Citation represents the impact and the influence of the articles, so this high citation trend indicates that the nanotechnology articles generated by South African researchers are of good quality.

Table 16. South Africa publication and citation trend and growth rates for 2005 - 2015

Year	Total articles	N&N articles	Growth rates	Total citations	N&N Citations	Growth rates
2005	6409	62		129563	18	
2006	7310	64	3.22	131899	156	940
2007	8569	83	29.68	129236	365	133.97
2008	9560	122	46.98	143538	671	83.84
2009	10602	163	33.60	137147	997	48.84
2010	10936	238	44.17	139804	1477	48.14
2011	12563	279	17.22	126577	2211	49.69
2012	14311	343	22.94	121541	2858	27.78
2013	14890	456	32.94	94893	4048	41.63
2014	16260	521	14.25	75991	5662	39.87
2015	17246	597	14.58	35174	7229	27.68

South African publication output in N&N during the period 2005 - 2015 consists of 2928 publications. In terms of publication, the nanotechnology area has increased at an average annual growth rate (AAGR) of 25.95%; the citation did even better with the AAGR of 144%. This growth is in line with the international growth in N&N, which has been reported to be at 23% and quite significantly higher than the average annual growth rate of publications in South Africa in general, which is 14% (Roco, 2011). The growth rate for N&N articles in 2006 was 3.2% in 2006; this accelerated sharply to almost 30% in 2007 and up to 46% in 2008. This area was growing at a fast pace, finally stabilising at about 14% in 2014 and 2015. It will be interesting to observe how the growth evolves in the next few years or whether 14% is the new normal, as it is in line with the growth of South African publication in general. The citations for N&N articles grew off a small base of only 18 citations in 2005 to 156 citations in 2006, a 940% increase. This growth began to decelerate, finally settling at about 48% in 2009 to 2011. The citations are still growing rapidly with a growth of 27% in 2015, however, this growth is as high as in the earlier years. The growth of nanotechnology, both in terms of articles published and the citations they received, is phenomenal, indicating that the researchers are spending resources in this field of research, and probably the government support initiatives are successfully stimulating interest in this area.

Table 17 shows the publication trend of nanotechnology articles in other selected countries for comparison purposes from the year 2005 to 2015. The ratio of N&N articles produced to total articles in all areas is a useful means of comparison, as well as the activity index. The totals are obtained using InCites™ , an analytical tool also provided by Thomson Reuters, which uses the same Web of Knowledge database.

Table 17. N&N publications totals compared to selected countries for 2005 to 2015

	N&N articles	Total articles	Ratio	Activity index
World	996 083	15 914 248	0.062	1
China	220 413	2 335 407	0.094	1.50
USA	165 691	6 205 056	0.027	0.43
India	49 981	603 489	0.083	1.32
Russia	23 755	372 700	0.064	1.01
Brazil	11 878	439 444	0.027	0.43
Egypt	5 236	80 346	0.065	1.04
South Africa	2 928	122 126	0.024	0.38

Looking at table 17, South Africa compared with the other BRICS countries, Egypt and the other leading countries in nanotechnology, the USA has a lower emphasis N&N with only 2.4% of publications being in the nanoscience field. South Africa's share of N&N articles over this period in the world is 0.29%, far below 0.79%, which is the share of total South African articles to the world total. This may indicate that N&N research output has most likely not reached its full potential. N&N is a high growth research area internationally, and the growth in the number of South Africa publications is not keeping up with the growth in the overall growth of the field worldwide. Egypt produced 5236 publications over this period, placing this country in a leading position in the African continent in N&N. Chen *et. al.* (2009) found that for the three countries, Russia, India and China, from 2000 to 2007, rapid growth of about 12.8 times in China, 8 times in India, and 1.6 times in Russia were recorded in terms of N&N publications. What is apparent is that N&N is growing very rapidly while the growth in South Africa has been recorded to be below that of other countries. Appelbaum *et. al.* (2011) confirms the importance of nanotechnology in China with several state-led interventions. The Chinese government is also investing an estimated $200 million per year in this field, making it only second to the United States. The United States launched its Nanotechnology Initiative in 2000 and the annual budget for 2016 is estimated at just over $1.4 billion, while the Chinese government followed a year later with its own initiative in 2001. In both countries, the N&N initiatives were accompanied by big dedicated budgets (Sergent, 2014). South Africa only launched a similar initiative in 2005 with what can be described as a very modest budget. It is interesting that China, India, Russia and Egypt show figures above 1, which is an indication that these countries have placed more emphasis in N&N. Despite a higher budget, the USA, along with South Africa and Brazil, have the activity indices of less than 1, showing no specialisation in this field. Besides looking at the number of publications, another indicator for the comparison with other countries is the activity index; first described by Frame (Frame, 1977). It indicates the country's relative share in world publications in a particular field of science, to the overall share in world total publications. This has been used quite recently in other studies, such as the one by Makhoba & Pouris (2016), where different scientific priority areas in South Africa were compared. The activity index is zero when the country holds no publications in that discipline, and it is equal to 1 if the country's share in the discipline equals the country's share in all fields indicating no specialisation, and above 1 when a positive specialisation is observed.

7.3 COLLABORATION AND PUBLICATION PROFILING OF SOUTH AFRICA

In this section, the collaboration with researchers from other countries is examined for the nanotechnology field, as indicated by co-authorship of research papers. The top 25 countries based on the co-authored articles are mentioned in figure 17.

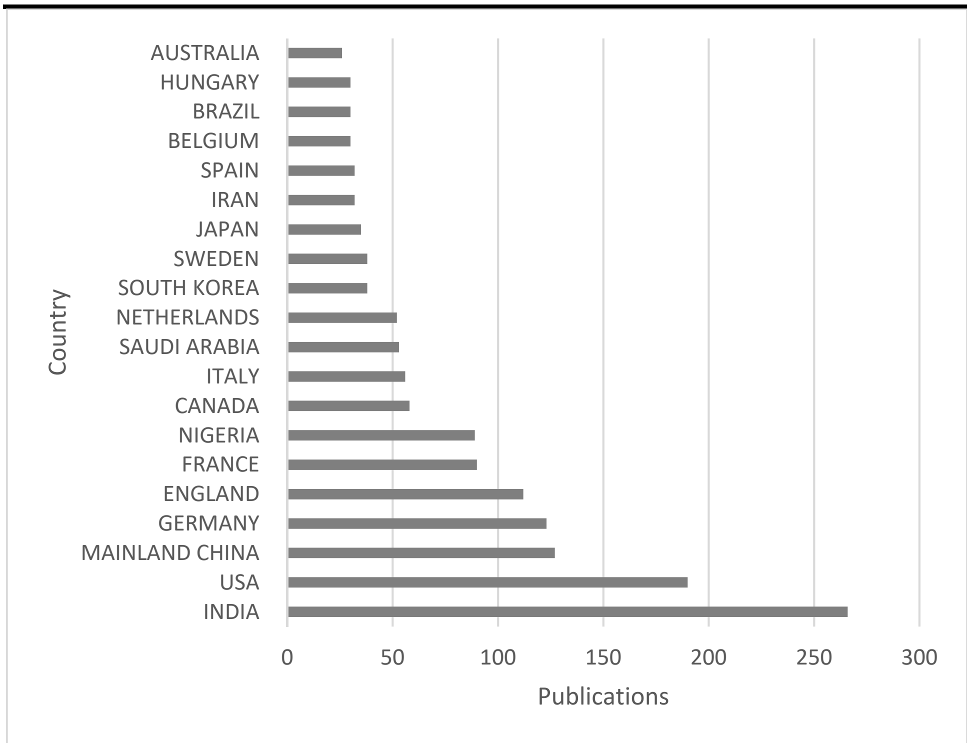

Figure 17. Nanotechnology collaboration profile of South Africa with other countries

The results on Figure 17 indicate that collaboration with India in the nanoscience and nanotechnology research area is the highest, which is followed by USA then China. In terms of the numbers, South Africa produced publications in collaboration with the countries as follows during the 10 years: India (266 publications), United States (190 joint publications), China (127 publications), Germany (123 publications) and England (112 publications). Their aggregate share of collaboration with these top five collaborating countries (818 publications) is actually 28% of the total number of all publications. United States is a global leader in the nanotechnology field, and consequently is a key country to collaborate with in this field. In general, South Africa collaborates more with Americans, followed by England and then Germany, so the discovery that in N&N the trend is quite different is surprising (NACI,2016). While the presence of India as the top collaborating partner may come as a surprise, South Africa has strong historical ties with India that predates their involvement in the BRICS grouping. Finardi (2015), in a study of the BRICS countries, found that South Africa and India have the strongest collaborations compared to other countries in the BRICS grouping. This was attributed to both countries belonging to the Commonwealth, both being part of the British Empire and both sharing English as one of the official languages.

The results are not expected to add up to 100% since most of the articles are produced exclusively by South Africans without an external collaborator. It is important to note that within the continent, South Africa has less collaborations with other African countries, with only nine countries that are in the African continent. The collaboration with other African countries produced a total of 130, accounting for only 5.57% in this field in South Africa. Collaboration with Nigeria, which is South Africa's biggest collaborator in Africa in this area, only produced 58 articles, which is low compared with India, for example. This is hardly surprising since it has been established in past studies that African researchers prefer to collaborate with researchers outside of the continent. Pouris and Ho (2013) found that South African researchers have been increasingly publishing with international partners with a growth of 66% in the five years between 2007 and 2011, making up a total of 54% of all articles produced in the country. This growth is on the back of the findings by Boshoff (2009), showing that collaboration with the neighbouring countries in Southern African Development Community (SADC) has remained stagnant at 3% for the 3 years between 2005 and 2008.

7.4 NANOTECHNOLOGY JOURNALS USED BY SOUTH AFRICAN RESEARCHERS

Table 18 highlights the top 25 journals where N&N publications by South African researchers are to be found. Included is the journal impact factor as published in the journal citation reports by Clarivate Analytics (formerly Thomson Reuters) for year 2015. Of the journals below, 48 are in English language and the rest are multilingual.

Table 18. Nanotechnology journals used by South African researchers

Source Titles	Impact factor	Record Count	Country
Electrochimica acta	4.803	62	England
Journal of Nanoscience and Nanotechnology	1.338	61	USA
International Journal of Electrochemical Science	1.692	54	Serbia
Materials Science	0.143	51	Ukraine
Journal of Applied Polymer Science	1.866	47	USA
RSC Advances	3.289	41	England
Journal of Alloys and Compounds	3.014	39	Switzerland
Applied Surface Science	3.150	36	Netherlands
Physica B condensed matter	1.352	33	Netherlands
Journal of Materials Science	2.302	32	USA
Polyhedron	2.108	32	England
International Journal of Hydrogen Energy	3.205	30	England
South African Journal of Science	0.902	29	South Africa
Polymer	3.586	26	England
Carbohydrate polymers	4.219	25	England
Journal of power sources	6.333	25	Netherlands
Materials chemistry and physics	2.101	25	Switzerland
Electroanalysis	2.471	24	Germany
Optical materials	2.183	23	Netherlands
Journal of Luminescence	2.693	23	Netherlands
Journal of Nanoparticle research	2.101	22	Netherlands
Journal of Photochemistry and Photobiology A chemistry	2.477	21	Switzerland
New Journal of Chemistry	3.277	21	England
Thin Solid Films	1.761	21	Netherlands
Applied Catalysis A General	4.012	20	Netherlands

Table 18 contains the top 24 most preferred journals in nanotechnology research in South Africa during 2005-2015. The South African authors published most of the journals of *Electochimica Acta* with 62 articles, followed by the *Journal of Nanoscience and Nanotechnology* with 61 articles and, lastly, the *International Journal of Electrochemical Science* with 54 records published in this journal. The top 25 journals have a significant 27 (803) of the total of published records. This indicates a wide scatter of literature in nanotechnology with no clear concentration of articles in one group of journals. In this list, the low representation of South African journals is observed, indicating a preference for international journals, with only the *South African Journal of Science* represented in the top 25 list. The most used language in the top 25 journals is English, with the rest being bilingual, showing the dominance of this language in South African research.

Most of the journals are from Netherlands followed by England and with the countries having eight and seven journals on the top 25 list, respectively. In the age where communication is facilitated quite easily through the internet the contry whre the journal is base should not matter language is a more important. The USA, with which South African researchers collaborate the most, only has three publications on this list. Therefore, it is clear that South African researchers are leveraging international resources to catch up in nanotechnology research. Additionally, they attempt to increase the visibility by publishing most of their articles in journals from European countries but still collaborating with the USA. The journals range from the lowest, the impact factor of 0.143 for the *Material Science* journal from Ukraine, to the highest, being 6.333 for the *Journal of Power Sources* from the Netherlands. The average impact factor for the journals listed in Table 18 is 2.60, as published in the 2015 Journal Citation Report by ISI.

7.5 SUBJECT AREA STRUCTURE

To understand the subject area structure, the analysis of publications and their subject categories is done; this is presented in table 19.

Table 19. Nanotechnology subject area map in South Africa

Research Areas	Record count	% of total
Chemistry	1089	37.19%
Material Science	910	31.08%
Physics	605	20.66%
Science technology and other topics	383	13.08%
Polymer Science	338	11.54%
Engineering	289	9.87%
Electrochemistry	278	9.50%
Pharmacology Pharmacy	105	3.59%
Environmental Sciences Ecology	100	3.42%
Energy Fuels	91	3.11%
Metallurgy and Metallurgical Engineering	82	2.80%
Optics	76	2.60%
Biochemistry Molecular Biology	75	2.56%
Crystallography	57	1.95%
Water Resources	57	1.95%
Instruments & Instrumentation	56	1.91%
Biotechnology and applied microbiology	54	1.84%
Mechanics	48	1.64%
Thermodynamics	44	1.50%
Nuclear science and technology	31	1.06%
Spectroscopy	28	0.96%
Mathematics	26	0.89%
Biophysics	22	0.75%
Toxicology	22	0.75%
Microbiology	21	0.72%
Geology	20	0.68%

The N&N publications are analysed according to subject area, this is shown in Table 19. The highest number of publications by South African researchers fall into the threes traditional domains, which are Chemistry, Physics and Material Science. The top three subject areas account for 88.9% of the country's publications in the field of nanoscience and nanotechnology. It is clear, therefore, that most of the nanotechnology applications are in Physics, Chemistry and Materials Science. The priority application areas that are emphasised in the South African N&N strategy, such as water, health and energy, seem well presented although not to the extent envisaged in the strategy. It is also interesting that there is a broad spread in terms of the application of nanoscience and nanotechnology, including areas such as Mechanics, Optics and Geology. The results are not expected to add up to 100% since most of the articles can belong to more than one research domain and only the top 25 fields are reported. An interesting feature which was not addresed is on the nanotechnology journals do not appear in this list and were not visible for the and the reasons why South African researchers publish in these, this could prove useful for future research.

7.6 PUBLISHING ORGANISATIONS

This section gives an overview of the most prolific institutions in N&N in South Africa over the period under review [Table 20].

Table 20. Most prolific organisations in nanotechnology publishing in South Africa

Organisation	Record Count	% of total
CSIR South Africa	479	16.36%
University of Witwatersrand	416	14.21%
National Research Foundation	397	13.55%
University of Johannesburg	381	13.01%
University of Western Cape	269	9.19%
Rhodes University	264	9.02%
University of KwaZulu Natal	249	8.50%
University of the Free State	244	8.33%
University of Pretoria	218	7.45%
Stellenbosch University	215	7.34%
Tshwane University of Technology	158	5.40%
University of South Africa	133	4.54%
University of Cape Town	120	4.10%
North West University	104	3.55%
University of Zululand	87	2.97%
Nelson Mandela Metropolitan University	75	2.56%
MINTEK	71	2.43%
Cape Peninsula University of Technology	50	1.71%
Vaal University of Technology	43	1.47%
Durban University of Technology	42	1.43%
University of Fort Hare	28	0.96%
Walter Sisulu University of Technology	24	0.82%
University of Limpopo	23	0.79%
Sasol Technology	15	0.51%

Analysis of the results in Table 20 indicates a dominant contribution of institutions based in Gauteng province with three of the top five based in this province. It is unclear whether this was a deliberate policy objective from the government perspective or a coincidence.

The N&N strategy is silent on this issue. The Council for Scientific and Industrial Research (CSIR) accounted for 16.4% of publications in the N&N area, followed by the University of the Witwatersrand (Wits), which is at 14.2%. The government, through the Department of Science and Technology, established and funded the Nanotechnology Innovation Centre, sometimes referred to as the Centre for Nano-Structured Materials, based at the CSIR, and this explains the CSIR's leadership role in this field. The centre at the CSIR, called the National Centre for Nano-Structured Materials (NCNSM), is one of two Nanotechnology Centres established by the government in 2007. Its focus is on the development of new nanotechnology enabled materials, with applications in the manufacturing, water and health sectors. The NCNSM as a government-funded institute makes available high-tech instrumentation to other researchers in South Africa. The other national centre is based at Mintek and focuses on the fields of sensors, biolabels and water treatment nanotechnologies. Interestingly, the NRF also features strongly in the third position with most of the output attributed to the national facilities, notably iThemba LABS.

Table 21. The two most prolific N&N institutions in South Africa and collaborative partners

CSIR South Africa		**University of Witwatersrand**	
Collaborating Institution	Number	Collaborating Institution	Number
University of Johannesburg	80	NRF South Africa	169
University of Pretoria	69	University of Johannesburg	54
Tshwane University of Technology	56	CSIR South Africa	46
University of the Western Cape	52	MINTEK	27
University of Witwatersrand	46	University of KwaZulu Natal	18
University of the Free State	45	Vaal University of Technology	18
University of South Africa	31	Universidad Federal do Parana	13
NRF South Africa	50	Tamkang University	11
King Abdulaziz University	21	Ulster University	11
University of KwaZulu Natal	19	University of Malawi	9
North West University	17	University of South Africa	9

In terms of inter-institutional collaboration, the most prolific institutions in N&N research in South Africa collaborate with each other extensively, as indicated by the number of co-authored articles [table 21]. The CSIR, out of a total of 479 publications, collaborated with UJ (80), UP (69) and TUT (56) nationally and internationally with the King Abdualaziz University in Saudi Arabia (21) and the University of Malawi (11). This is not surprising as the first three institutions are in Gauteng Province the same as the CSIR; the close proximity facilitates collaboration. The CSIR is also a national facility providing access to analytical equipment to researchers countrywide, and therefore the high number of papers co-authored with researchers from other South African institutes. In the case of Wits University, out of a total of 420 publications, collaborated with NRF (169), UJ (54) and CSIR (46) nationally and internationally with the Universidarde Federal do Parana in Brazil (18), Tamkang University in Taiwan (11) Ulstar University in the UK (11) University of Malawi (9). Clearly, an argument can be advanced that the institutes from the Gauteng province, South Africa's economic hub, are leading, and it looks like there is a close level of collaboration between them. It would seem that despite its relatively small scientific size, Malawi, through the University of Malawi, has a very close relationship with the two top South African institutes in N&N research.

However, based on information in Table 20 and Table 21, there is an obvious lack of representation from the private sector with only Sasol Technology having some publications in this field. This does not augur well for the future commercialisation of nanotechnology-enabled products in the country as envisaged in the N&N strategy. Perhaps this could be explained in that the private sector may prefer the patenting route or trade secret rather than disseminating their research findings through publications.

7.7 CONCLUSIONS

Due to the growing technological significance and expected economic contribution, N&N in South Africa has been thoroughly analysed through bibliometric methods. The research output of South Africa is showing a steady increase since the introduction of the Nanoscience and Nanotechnology Strategy in 2005, and the associated government support. However, to put this into context, there is a need to look at some of the other countries, Egypt, for example, during the same period produced almost double the amount of publications in South Africa. Looking at the other BRICS countries, China produced 220413, India 49 981 Russia 23755 and Brazil 11878 articles over this period. The US, on the other extreme, produced a total of 165691 articles during this period, in line with their big budget for NNI which is projected to reach US$1.5 billion in the year 2016. This discrepancy may be partly due to the country's low budget for R&D in general, but also lack of prioritisation of N&N in the country. This lack of prioritisation is evident when one looks at the low activity index, with Egypt having taken a leading position in this field in the African continent. So, in conclusion, the policy from the government side has managed to institutionalise N&N research within the science councils and most of the universities as opposed to what was the case before the introduction of the strategy. This, however, is not sufficient. The country has a potential to produce more output in the N&N based on the comparison with output from other science areas. In a comparison of the OECD countries, it has been found that in 2014, the GERD as a percentage of GDP was 0.73% for South Africa, whereas the average for OECD countries is 2.38%; interestingly, for China this value stood at 1.93% for 2014 (OECD, 2014). Therefore, there is a clear underinvestment in research and development in South Africa in general, not only in N&N research. The CSIR emerges as the most productive institute in N&N research and this can be attributed largely to the direct and continuous government investment in this organisation by, for example, establishing the Centre for Nanostructured Materials. However, innovative outputs, such as new nano-enabled products, as envisaged in the N&N strategy, will be difficult to achieve with a low level of research and collaboration in this field by the private sector. The introduction of R&D tax incentives in South Africa is a means to encourage an increased participation of the private sector in research and development. The lack of private sector involvement can, in part, be ascribed to the early stage of nanotechnology development in South Africa, with most research efforts geared to generating knowledge in the field. A more likely reason is the generally weak domestic corporate research and development expenditure, since, currently, the country's gross expenditure of research and development (GERD) as a percentage of GDP of 0.73 is made up of only a small fraction from the corporate sector, as measured in 2014. In South Africa, the business expenditure of research and development (BERD) as a percentage of GDP stands at 0.32 and this is against the OECD average of 1.58, whereas that of China is 1.47, showing that the country is lagging. Future work will need to look at a quantitative comparison of this output with other developing countries and possibly providing an analytical perspective of low patenting trends in this field.

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CHAPTER 8 ANALYSIS OF R&D EFFICIENCY IN SOUTH AFRICA: A COMPARISON WITH OTHER BRICS COUNTRIES

8.1 INTRODUCTION

In this chapter, the efficiency of South Africa's system of R&D is analysed through the assessment of outputs against inputs. Measuring the returns to R&D has undoubtedly been a major issue in innovation studies for monitoring and evaluation of the national/regional systems of innovation (NSI) (Beneito, Rochina-Barrachina & Sanchis, 2015). In any case, metrics that measure the comparison of inputs against outputs are widely used in such studies. The purpose of this research is to assess and compare the R&D efficiency of the two priority research areas in South Africa, namely biotechnology and nanotechnology. Nanotechnology and biotechnology have received a lot of attention because of their cross-cutting nature and their potential impact in stimulating economic growth through creation of new emerging industries. It is for this reason that the government has placed them on top of its priority list in science and technology. The identification of weaknesses and recommendations on their correction may assist in ensuring the efficient allocation and utilisation of scarce resources. These areas are chosen as they are explicitly mentioned in the South African R&D strategy (2002), the Ten-year Innovation plan towards a knowledge-based economy for South Africa (2008) and other government documents. The aim is to establish developments in the identified fields as to whether South African research output is aligned with the S&T strategic objectives of the country, to establish the current status of these areas, and to establish the progress made so far, including the relative progress of each area in South Africa. The results are then presented in this section.

The secondary data collected is presented on the inputs (expenditure) and outputs (publications and patents) from the R&D process of the two areas of research, biotechnology and nanotechnology, in South Africa. This data is further used in the computation of R&D efficiency.

8.2 R&D EFFICIENCY IN SOUTH AFRICA

To analyse the R&D efficiency in South Africa, we first look at its efficiency in production of patents and publication for all the scientific fields (total), versus its production in the field of nanotechnology and biotechnology.

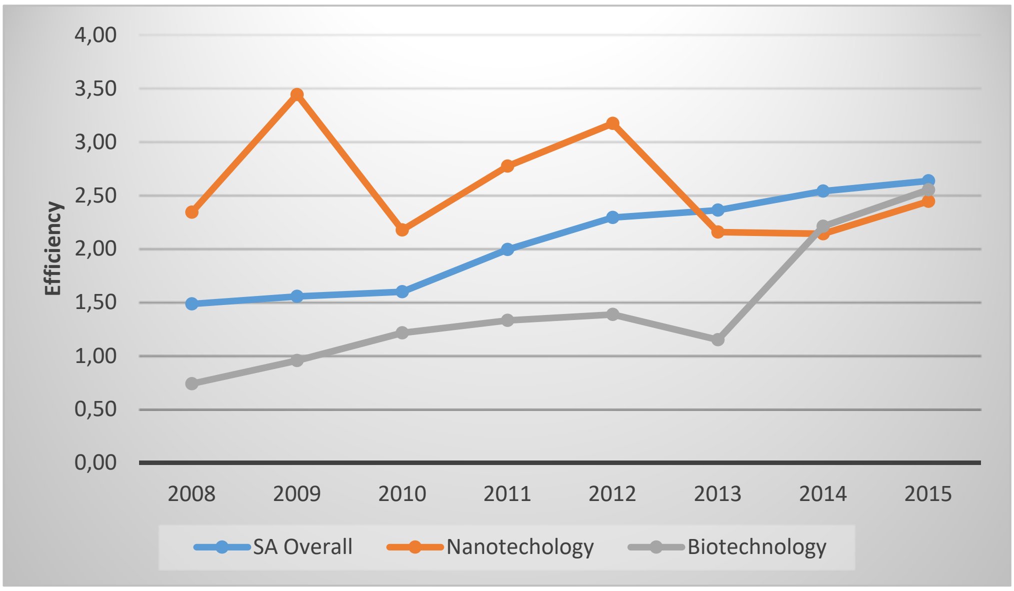

Figure 18. A graphic presentation of the R&D efficiency (publications) trend for each of the two priority areas in South Africa

Figure 18 illustrates the R&D efficiency trend for South Africa in terms of publications produced in each research area per million US$ spent on R&D. South Africa's efficiency in terms of the two priority areas is analysed and is compared with the output in all scientific areas. The results expressed as articles published per US$ million spent on expenditure show the varying performance in these fields. Biotechnology improved its efficiency from 0.74 publications per US$ million in 2008 to 2.5 publications in 2015 per million US$ - a remarkable improvement. In terms of the total scientific publications, the country was producing 1.5 publications per million US$ spent on R&D; this improved to 2.6 publications per million US$ in 2015. Nanotechnology productivity is quite high, reaching 3.5 in 2008, it seems to be stabilising around 2 publications per million US$ spent. Amongst the priority areas, South Africa seems to differ substantially, while in terms of publications, the picture does not seem to be bad at all over the monitoring period.

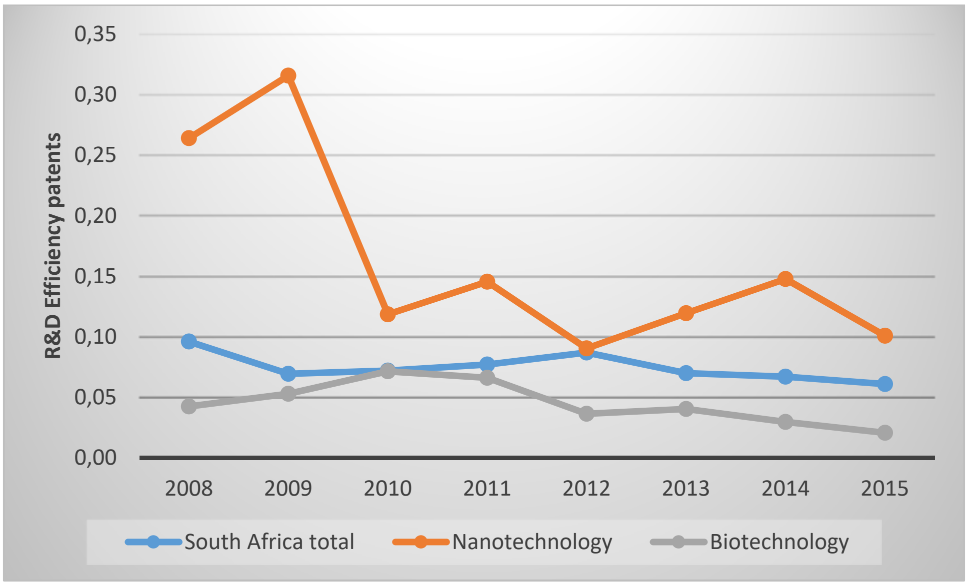

Figure 19. A graphic presentation of the R&D efficiency (patents) trend for each of the two priority areas in South Africa

Biotechnology seems to have the lowest level of patenting efficiency in South Africa (Figure 19). South Africa, in general, generates less than 0.1 patent per US$ million it spends on R&D. The picture looks better than that in nanotechnology where the country was producing 0.3 publications per million US$ in 2008. This has somewhat deteriorated on 0.1 patent per million US$ spent on research and development. This shows that in terms of value for money overall, the country is getting less than it used to in 2008 for the same amount of expenditure.

8.3 R&D EFFICIENCY WITHIN THE BRICS COUNTRIES

In this section, South Africa is compared to the other BRICS countries in terms of patents granted and publications per US$ million spent on expenditure.

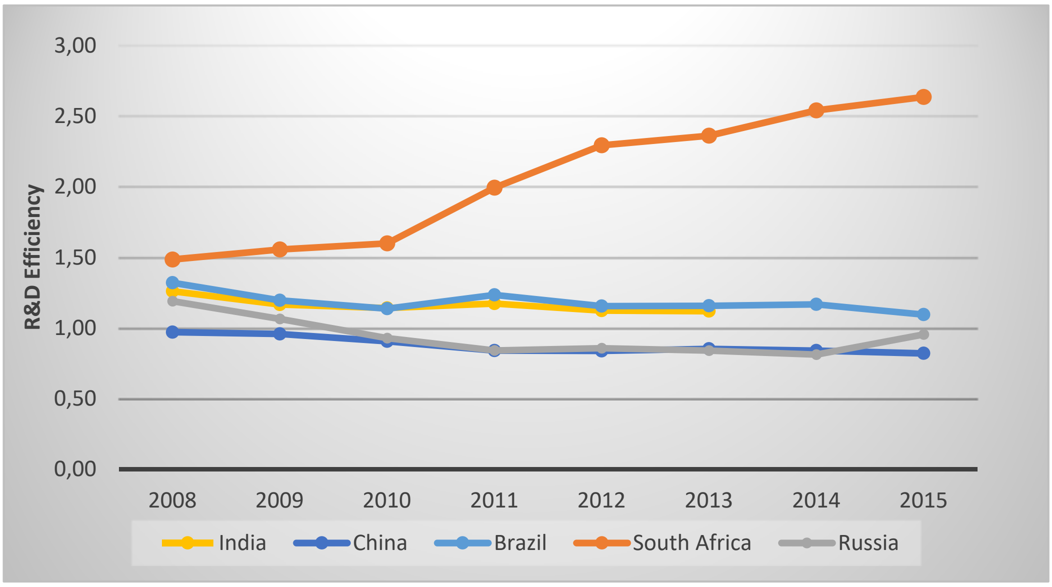

Figure 20. A presentation of the R&D efficiency (publications) trend for the BRICS countries

Figure 20 illustrates a R&D efficiency of the BRICS countries as measured through publications per million dollars spend on R&D in each of the BRICS countries. From a publication standpoint, China seems to be getting the least outputs per US$ spent at less than 1 publication per US$ million over the entire period. South Africa, on the contrary, seems to have been increasing its efficiency from 1.5 publication in 2008 to just above 2 publications in 2015 per million US$ spent on R&D, ranking it the most efficient amongst the BRICS.Amongst the BRICS, South Africa seems to differ substantially while most of the BRICS countries have experienced a deterioration over the years within the monitoring period.

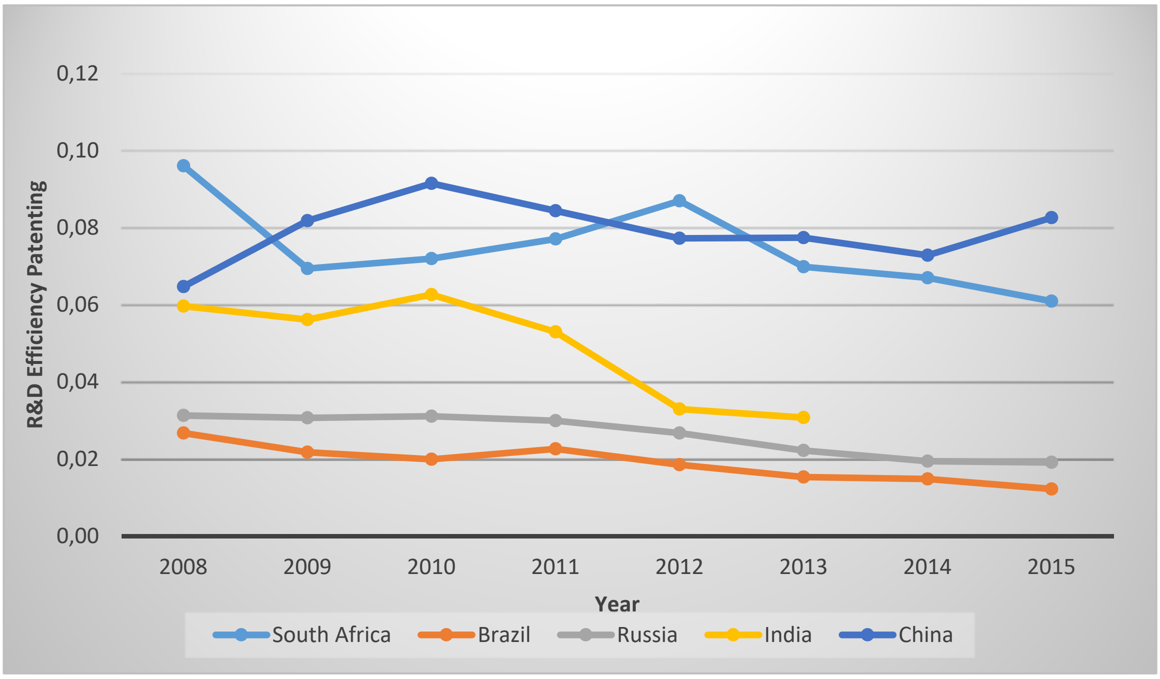

Figure 21.A presentation of the R&D efficiency (patents) trend for the BRICS countries

Figure 21 illustrates R&D efficiency of the BRIC countries as measured through patenting per million dollars spend on R&D in each of the BRICS countries. If patenting alone is considered, Brazil followed by Russia seem to have the lowest R&D efficiency, while South Africa followed by China seem to have higher efficiency. The efficiency seems to be deteriorating though, with South Africa having an efficiency of 0.1 patent per US$ million in 2008 into less than 0.06 patent per million US$ spent on research and development. What is also clear is that the trend is downwards, amongst all the BRICS countries the patenting output per dollar spent is going down every year. This shows that while R&D expenditure is increasing in nominal terms, this is not matched by a comparable increase in patents outputs.

8.4 CONCLUSIONS

South Africa has a goal of strengthening local capacity in the two fields of nanotechnology and biotechnology to benefit from the knowledge intensive economy. Both fields seem to be struggling to produce patents, while the publications trend is an upward trend. This may indicate that there is an overemphasis of academic research rather than industrial research, which should not be ignored when one considers the goals of developing a thriving industrial cluster around these technology fields. What may be surprising is that the country seems to be more efficient in transforming the scarce financial resources compared to its bigger BRICS partners that have thriving technology-based industries. This may offer opportunity and lessons to the bigger countries. The limitations must be noted in that the current research measures only a few variables in a very complex environment. In this system, there are multiple actors, inputs and outputs, and, therefore, our simplified analysis may not account for other outputs besides patents and publications. It may just turn out that the focus of the different programmes is on different outputs, such as start-ups and spin-off companies instead of the bottom up development of technology, as technology can also be imported by means of, for example, purchasing a patent or technology license and then deploying the technology locally. In addition the expenditure data includes the private sector investments and some private institutions do not necesarilly invest in R&D activities with an expectation of academic publications.

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CHAPTER 9 CONCLUSIONS

9.1 INTRODUCTION

In this chapter, conclusions are drawn regarding the specific objectives of this study. The limitations of the research are discussed, followed by recommendations regarding future research. This chapter, which is the final chapter of the study, summarises the conclusions and recommendations relating to the findings of Chapter 5, 6, 7 and 8. Conclusions are made based on the analysis of results obtained in the research. The recommendations offered then follow the conclusions drawn in the research and is accompanied by the recommendations for other areas of future research.

9.2 CONTRIBUTION

The scientometric study of focus areas in South Africa considered in this study was done using patents and publications. The first part of the study looked at publications and considered only four priority areas, which are biotechnology, energy, palaeontology and astronomy using activity and attractivity indices as relevant scientometric indicators. The study shows that in the niche areas where the country has a geographic advantage, such as palaeontology and astronomy, the country is doing extremely well. This can, in part, be attributed to the ability of the country to attract international researchers who are eager to collaborate with local researchers in these fields in which South Africa enjoys a geographic advantage and has a long history of participation.

Biotechnology and energy seem to be relatively small areas of research in the country, the growth has been intermittent; one year there is an improvement, and the other year the trend is downward. In terms of biotechnology, it is deemed that the problem may be based on the strategy approach. The strategy emphasised the development of commercial products through the biotechnology innovation centres that were established, and a lot of funding was directed to these. It is important in any field to build the intellectual base through which basic research can be pursued, which will gradually lead to translation to products. The result in terms of energy are quite puzzling. South Africa is a very energy intensive country, as shown earlier, but seemingly, there is very little academic research in this field. It therefore looks like South Africa will import most of the technology used for energy production, an observation that is counter to the goals of the 10-year plan towards an innovation-based economy. It is therefore recommended that in developing these areas investment in relevant human capital development and academic research should not be ignored as these affect the outcomes. Otherwise, based on the research questions, a clear picture in terms of the performance of these areas relative to each other and the peers in the other BRICS countries has been provided.

The second part of the study was to investigate the patenting trends within the identified priority areas. In terms of patenting trends within the South Africa, the study looked at those areas with some patents registered. The areas that seemed to have a critical mass of patents were considered, and these are biotechnology, ICT, nanotechnology, energy and health. Other areas could not be considered because there are hardly any patents that could be found. In general, South Africa is not doing well in terms of patenting. Considering its intellectual capacity, as expressed earlier using publications in general, there is a low level of patenting in the country. One argument is that the strengthening of the domestic patent office (CIPC) may help entrench a culture of patenting technology inventions.

The third part of the study looked at the fast-developing areas of R&D and its implementation in South Africa; N&N research. In terms of lessons from N&N development, it is clear that this relatively new area of research has had a relatively good uptake from the research community. What may have been the advantage is that the strategy development was largely driven by the nanotechnology community under the SANI organization. The strategy emphasised the holistic development that included recommendation that implementation for the initial years should focus on human capital development in the form of Master's and Doctoral students training, as well as investments in infrastructure. Government funding was similarly structured to cater for these requirements and, as a result, while the country has not done well in terms of patents in this area, it has done well in terms of quantity and quality of research output. It will be interesting whether an upward trend in terms of patenting will be observed in the next few years.

Another indicator that was studied was the R&D efficiency in these priority areas. This provided an insight on whether the resources that are currently committed to these priority areas are being used effectively and appropriately. One challenge is that while output data in a form of patents and publications is readily available, input data, for example, on R&D expenditure per research focus area, by both government and private sector, is not readily available. Fortunately, the South African government, through the HSRC, has started to collect expenditure data for its two high priority areas; these are biotechnology and nanotechnology. The study, therefore, compared the output per unit expenditure in these research areas. In addition, the output of South Africa in all scientific areas was compared to the BRICS countries. Nanotechnology, compared to biotechnology, produces more patents for equivalent funds spent. However, when one considers publications while nanotechnology was producing more historically, they were in almost equal basis towards the end of period of study. Additionally, it was found that on both publications and patents, South Africa tends to produce more than its BRICS counterparts per unit expenditure on R&D.

What seems clear is that the R&D policies have not stimulated the translation of research into patents in general; the patenting trends from all fields is very low. This speaks to the lack of industrial involvement in research in South Africa as shown by the data. Therefore, according to the innovations model, more efforts need to be put into stimulating this sector of the economy as virtually all models discussed in chapter 2, including the TENs and the Triple helix, emphasise the role of industry in addition to government and academia. The TENs model emphasises that government has many limitations in terms of direct impact on R&D-based innovation, as the role it plays is indirect. Additionally, the South African system of innovation tends to not respond to the changes in the external environment, for example, the NRF researcher rating system has not changed despite evidence that it may be biased and there are better technology-based systems for evaluation, for example (Callaghan; 2018). This tool is very instrumental and influences funding decision and career progression. The current system is objective and incentivises narrow focus research area, the so-called monodisciplinary focus, and may favour established institutions, which is not ideal in the country given its past. Based on this, it is uncertain that the country will achieve its objectives, especially in the applied technologies that tend to be interdisciplinary.

9.3 LIMITATIONS

This type of study, due to the broader scope, will always have some kind of limitations. This relates firstly to the definition of priority areas. The priority areas are very broad, and some are amorphous; very difficult to analyse objectively. The countries priority areas are many, to be frank, and some are yet to produce outputs and, therefore, cannot all be studied. Areas such as improved quality of life, food security and poverty alleviation are worthwhile goals for government to address. However, these need to be defined further, as to what will be contribution of R&D so that they are scientifically measurable to enable valid investments and analysis of the progress.

The statistics collected by the Human Sciences Research Council, as contained in the R&D survey (HSRC, 2016, NACI 2016), provides statistics on the numbers of PhD graduates, patents and publications in general, and overall terms. What would be more useful, would be to measure for these outputs for each of the indicators and for each of the priority areas, as mentioned in the R&D strategy before summation. This has its own challenges, such as the overlap between research areas; some research output may belong to more than one research area, for example, both nanotechnology and biotechnology, and this will present difficulties to data collectors.

This thesis discussed different technologies and their current state in South Africa compared to other BRICS countries. These technologies have particular significance currently; however, one wonders what the future holds for the priority areas especially with the advent of convergence of technologies and industry 4.0. In the era of converging technologies, it will become increasingly hard to distinguish between different disciplines especially those that are related to industrial applications. This may yet again present certain policy consideration, as the applied technology will certainly require strengthening of foundational scientific disciplines while necessitating closer collaboration between disciplines. This represents a challenge in future from the policy perspective on how the different research areas are funded and incentivised.

9.4 FUTURE RESEARCH

Some of the mentioned focus areas have extremely low level of output, especially in terms of patents, and therefore could not be analysed at all. Other areas, as mentioned earlier, are poorly defined and therefore it is not easy to delineate these from other fields, and therefore a solution to this must be found. Most likely, the use of focus groups to obtain the consensus amongst the practitioners who encompass these areas will be useful. This will enable scientometrics to come up with proper schemes to classify documents that may belong to these areas, enabling proper study of these areas. However, on the policy front it is a concern that scientific output does not necessarily match the countries stated focus areas, especially those related to industrial competitiveness, which are energy and biotechnology. It will be interesting, in future, to consider other priority areas, such as global climate change research, when they reach a certain critical mass of research output, as this will impact the developing countries.

9.5 CHAPTER SUMMARY

In this chapter, an integrated conclusion of the patentometrics and bibliometrics study of the priority areas in South Africa and the comparator countries is given.

In Section 9.2, the summary of conclusions based on the findings from the different chapters is given based on the different metrics that were used in the study.

Section 9.3 points out some of the limitations of the current research, and 9.4 identifies areas of future research within the theme of this research.

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APPENDIX

A.1 THE METHODOLOGY FOR THE PATENTS RETRIEVAL BY PATENT CLASS

Area	*Search strategy*	*Reference*
Nanotechnology	Keywords	Maghreb, Abbasi, Amiri, Monsefi & Harati, 2011
Biotechnology	IPC codes 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)	Chen & Guan, 2011 Arts, Appio & van Looy, 2013 OECD, 2005
ICT	IPC Codes Telecommunication H04M Computer G06C Music G10 Camera G03B Navigation G01C	Curran & Leker, 2011
Energy	IPC codes C10G C10J C10K C10B B60K B60L F03G F25B F21J F24J E04D F24B H01L H02N H01M H02P F03D B63H B64C F01D F03G F01K F23G F23D A47J F01K F22B C21C F22B B60K F02B F02D F01K F02G F25D F25B F01B F01K C21D B22D C21B C21C D21C E06B E04C	Adapted from Popp, 2002
Health	IPC codes Medical Technology: A61 [B, C, D, F, G, H, J, L, M, N], H05G. and Pharmaceuticals: A61K not A61K-008	OECD 2009

Space & Satellite Technology	IPC codes B64G AND a keyword search on these classes B64, C06, F41, F42, G01, G08, H01, H02, H03, H04, H05 Using the keywords satellite", spacecraft", "rocket", "space", "launcher"	OECD (2011),

A.2 THE ORIGINAL METHODOLOGY FOR THE EXTRACTION OF ENERGY PATENTS (POPP, 2002)

Supply Technologies:

Coal Liquefaction:

208/400-435	Mineral Oils: Processes and Products/by treatment of solid material (e.g. coal liquefaction)

Coal Gasification:

48/200	Gas: Heating and Illuminating/Processes/Coal, oil and water
48/201	Gas: Heating and Illuminating/Processes/Coal and oil
48/202	Gas: Heating and Illuminating/Processes/Coal and water
48/210	Gas: Heating and Illuminating/Processes/Coal
48/71	Gas: Heating and Illuminating/Generators/Cupola/Coal, oil and water
48/72	Gas: Heating and Illuminating/Generators/Cupola/Coal and oil
48/73	Gas: Heating and Illuminating/Generators/Cupola/Coal and water
48/77	Gas: Heating and Illuminating/Generators/Cupola/Producers/Coal
48/98	Gas: Heating and Illuminating/Generators/Retort/Coal, oil and water
48/99	Gas: Heating and Illuminating/Generators/Retort/Coal and water
48/100	Gas: Heating and Illuminating/Generators/Retort/Coal and oil
48/101	Gas: Heating and Illuminating/Generators/Retort/Coal

Solar Energy:

60/641.8-641.15	Power Plants/Utilizing natural heat/Solar
62/235.1	Refrigeration/Utilizing solar energy
126/561-568	Stoves and Furnaces/Solar heat collector for pond or pool
126/569-713	Stoves and Furnaces/Solar heat collector
126/903	Stoves and Furnaces/Cross-Reference Art/Solar collector cleaning device
126/904	Stoves and Furnaces/Cross-Reference Art/Arrangements for sealing solar collector
126/905	Stoves and Furnaces/Cross-Reference Art/preventing condensing of moisture in solar collector
126/906	Stoves and Furnaces/Cross-Reference Art/Connecting plural solar collectors in a circuit

126/910 Stoves and Furnaces/Cross-Reference Art/Heat storage liquid

Solar Energy – Batteries:

136/206 Batteries: Thermoelectric and Photoelectric/Thermoelectric/Electric power generator/ solar energy type

136/243 Batteries: Thermoelectric and Photoelectric/Photoelectric

136/244-251 Batteries: Thermoelectric and Photoelectric/Photoelectric/Panel

136/252-265 Batteries: Thermoelectric and Photoelectric/Photoelectric/Cells

Fuel Cells:

429/12-46 Chemistry: Electrical Current Producing Apparatus, Product, and Process/Fuel cell, sub combination thereof or method of operating

Wind:

290/44 Prime-Mover Dynamo Plants/Electric control/Fluid-current motors/Wind

290/55 Prime-Mover Dynamo Plants/Fluid-current motors/Wind

416/132B Fluid Reaction Surfaces (i.e., Impellers)/articulated resiliently mounted or self-shifting impeller or working member/Sectional, staged or non-rigid working member/windmills

416/196A Fluid Reaction Surfaces (i.e., Impellers)/Lashing between working members or external bracing/Connecting adjacent work surfaces/Non-turbo machine (windmills)

416/197A Fluid Reaction Surfaces (i.e., Impellers)/Cupped reaction surface normal to rotation plane/Air and water motors (natural fluid currents)

Geothermal energy:

60/641.2 -641.5 Power Plants/Utilizing Natural Heat/Geothermal

Using waste as fuel:

110/235-259 Furnaces/Refuse incinerator

110/346 Furnaces/Incinerating refuse

Using waste gases as fuel:

431/5 Combustion/Process of combustion or burner operation/Burning waste gas, e.g. furnace gas, etc.

Ocean Thermal Energy Conversion (OTEC):

60/641.7 Power Plants/Utilizing natural heat/Ocean Thermal Energy Conversion (OTEC)

Renewable Energy – General:

60/641.1 Power Plants/Utilizing natural heat

60/641.6 Power Plants/Utilizing natural heat/ With natural temperature differential

Demand Technologies:

Waste heat:

122/7R	Liquid Heaters and Vaporizers/Industrial/Waste heat
7A	Liquid Heaters and Vaporizers/Industrial/Waste heat/Steel converter
7B	Liquid Heaters and Vaporizers/Industrial/Waste heat/Additional burner
7C	Liquid Heaters and Vaporizers/Industrial/Waste heat/Waste sulfate
7D	Liquid Heaters and Vaporizers/Industrial/Waste heat/Carbon monoxide
60/597-624	Power Plants/Fluid motor means driven by waste heat or by exhaust energy from internal combustion engine

Heat exchange – Refrigeration:

62/4	Refrigeration/Intermediate fluid container transferring heat-to-heat absorber or holdover/Flow line connected transfer fluid supply and heat exchanger
62/79	Refrigeration/Processes/Exchanging heat between plural systems e.g. Disparate
62/513	Refrigeration/Refrigeration producer/ Heat exchange between divers function elements
62/515-528	Refrigeration/Refrigeration producer/Evaporator, e.g. heat exchanger

Heat exchange – general:

165	Heat Exchange

Heat pumps:

62/238.7	Refrigeration/Disparate apparatus utilized as heat source or absorber/with vapor compression system/Reversible, i.e. heat pump
62/324.1-325	Refrigeration/Reversible, i.e., heat pump

Stirling engine:

60/517-526	Power Plants/Motor operated by expansion and/or contraction of a unit of mass of motivating medium/Unit of mass is a gas which is heated or cooled in one of a plurality of constantly communicating expansible chambers and freely transferable there between

Continuous casting:

148/541	Metal Treatment/Process of modifying of maintaining internal physical structure (i.e. microstructure) or chemical properties of metal, process of reactive coating of metal and process of chemical-heat removing (e.g., flame-cutting, etc.) or burning of metal/With casting or solidifying from melt/Iron(Fe) or iron base alloy/Continuous casting
148/551	Metal Treatment/Process of modifying of maintaining internal physical structure (i.e. microstructure) or chemical properties of metal, process of Reactive coating of metal and process of chemical-heat removing (e.g., flame-cutting, etc.) or burning of metal/With casting or solidifying from melt/Aluminum (Al) or aluminum base alloy/Continuous casting

164/263	Metal Founding/with product severing or trimming means/Associated with continuous casting means
164/268	Metal Founding/with coating means/associated with a continuous or semicontinuous casting means
164/415	Metal Founding/Means providing inert or reducing atmosphere/In-continuous casting apparatus
164/416	Metal Founding/Including vibrator means/In-continuous casting mold
164/417	Metal Founding/Combined/Including continuous casting apparatus
164/418-444	Metal Founding/Means to shape metallic material/Continuous or semicontinuous casting
164/445-446	Metal Founding/Starter bar
164/447-448	Metal Founding/Product supporting or withdrawal means for continuous casting apparatus
164/449.1-450.5	Metal Founding/Control means responsive to or actuated by means sensing or measuring a condition or variable (i.e., automatic control)/Control of feed material enroute to shaping area/Responsive to material level/In continuous casting apparatus
164/451-455	Metal Founding/Process/With measuring, testing, inspecting, or condition determination/Of continuous or semicontinuous casting
164/459-491	Metal Founding/Process/Shaping liquid metal against a forming surface/Continuous or semicontinuous casting
164/502-504	Metal Founding/Including means to directly apply magnetic force to work or to manipulate or hold shaping means/In-continuous casting apparatus
164/505-509	Metal Founding/Means to directly apply electrical or wave energy to work/In continuous casting apparatus
164/154.4	Metal Founding/Control means responsive to or actuated by means sensing or measuring a condition or variable (i.e., automatic control)/Responsive to position or spatial dimension/Responsive to rate of change/Continuous casting
164/154.5	Metal Founding/Control means responsive to or actuated by means sensing Or measuring a condition or variable (i.e., automatic control)/Responsive to position or spatial dimension/Continuous casting

Manufacture of aluminium – carbothermic:

75/10.27	Specialized Metallurgical Processes, Compositions for Use Therein, Consolidated Metal Powder Compositions, and Loose Metal Particulate Mixtures/Processes/Electrothermic processes (e.g., microwave, induction, resistance, electric arc, plasma, etc.)/Carbothermic reduction of Aluminium (Al) compound

Manufacture of aluminium – electrolysis:

204/67	Chemistry: Electrical and Wave Energy/Processes and Products/Electrolysis/Synthesis/From fused bath/Metals/Aluminium

Use of black liquor in paper manufacturing

162/31	Paper Making and Fiber Liberation/Processes of chemical liberation, recovery or purification of natural cellulose of fibrous material/with regeneration, reclamation, reuse, recycling or destruction of digestion fluid/Flames combustion
162/47	Paper Making and Fiber Liberation/Processes of chemical liberation, recovery or purification of natural cellulose of fibrous material/With heat recovery

Insulated windows:

52/172	Static Structures (e.g., Buildings)/Transparent panel; e.g., window, with treatment means/Hygroscopic material; e.g., internal drier
52/776	Static Structures (e.g., Buildings)/Window or window sash, sill, mullion, or glazing/Attaching means securing a pane to a sash member or to another pane/Solid three-sized glazing strip
52/788	Static Structures (e.g., Buildings)/Composite prefabricated panel comprising: separate mechanical fastener; means for support securement; disparate edging or stiffener which, in a multi-ply panel, extends outwardly of a major or edge face; or spaced sheets with in turned edge-forming flanges/Sandwich or hollow with sheet like facing members/Parallel, transparent panes, (e.g., double glass window panel, etc.)
52/790	Static Structures (e.g., Buildings)/Composite prefabricated panel comprising: separate mechanical fastener; means for support securement; disparate edging or stiffener which, in a multi-ply panel, extends outwardly of a major or edge face; or spaced sheets with in turned edge-forming flanges/Sandwich or hollow with sheet like facing members/Internal spacer

B. PATENT DATA IN BRIEF

Table B1. The patents found on WIPO for each of the South African priority areas

Year	Biotechnology	ICT	Nanotechnology	Energy	Health
2001	7	12	3	42	13
2002	11	14	4	37	13
2003	14	4	11	30	24
2004	8	16	10	21	9
2005	10	6	10	42	13
2006	9	4	9	42	22
2007	14	6	10	50	20
2008	13	11	7	38	16
2009	20	10	7	52	22
2010	19	7	10	38	19
2011	18	5	6	41	23
2012	10	3	12	37	17
2013	14	5	2	34	28
2014	9	5	2	40	16
2015	20	4	2	36	14
Total	196	112	105	580	269

Table B2. The patents found on WIPO for each of the priority areas in the BRIC countries 2001 - 2015

Country	Biotechnology	ICT	Nanotechnology	Energy	Health
Brazil	368	83	119	881	662
Russia	469	197	287	2 141	911
India	1 043	251	813	1 068	5 289
China	3 386	3 900	1835	11 506	6 106
South Africa	196	112	105	580	269
Egypt	21	13	15	83	60
World	53 4647	301 901	480 924	1 557 156	917 120

Table B3 Total patents found on WIPO for each of the BRIC countries by priority date

Year	World	South Africa	Brazil	Russia	India	China	Egypt
2001	1428958	450	234	615	574	881	4
2002	1274819	415	249	566	755	1272	19
2003	1222690	466	322	600	949	1724	29
2004	1252772	441	348	662	1089	2346	29
2005	1217557	463	365	690	1347	3824	45
2006	1125800	468	436	782	1507	5323	28
2007	1039020	470	556	780	1709	6488	38
2008	984028	440	579	716	1753	6828	38
2009	946722	338	562	814	1882	10160	48
2010	961257	371	575	934	2366	13362	40
2011	950458	371	652	1037	2128	15634	38
2012	913608	385	602	884	1439	16491	37
2013	816349	325	519	782	1477	19178	38
2014	515232	323	516	757	1375	21321	37
2015	69246	39	64	53	207	3132	2

Table B4. Worldwide patents in each of the priority areas

Year	Biotechnology	ICT	Nanotechnology	Energy	Health
2001	80929	40557	55024	162145	120627
2002	72638	34618	54872	149780	117136
2003	66562	34799	56143	147957	115290
2004	60684	34133	55123	144120	113598
2005	55683	29698	50514	128813	108776
2006	50091	27297	46465	122128	99460
2007	48471	23486	40951	120373	88788
2008	44874	21019	38142	116338	80056
2009	41450	18947	35104	121544	69931
2010	39649	19534	34639	131956	63252
2011	38815	19138	32346	132509	58830
2012	36704	18546	31669	129681	54781
2013	31851	16742	29073	111395	47106
2014	16424	11130	20776	72078	22695
2015	2064	1558	3571	12456	2795

C. DATA USED FOR THE CALCULATIONS OF R&D EFFICIENCY

C1. The inputs and output data for South Africa

C1.1 Inputs: R&D Expenditures US$ PPP Million

	Overall R&D expenditure	Biotechnology R&D expenditure	Nanotechnology R&D expenditure
2006	4 582,488	164,970	87,067
2007	4 872,277	170,530	63,340
2008	5 157,114	195,970	92,828
2009	4 813,704	211,803	96,274
2010	4 428,284	247,984	88,566
2011	4 652,174	223,304	125,609
2012	4 836,726	237,000	135,428
2013	4 956,719	242,879	128,875
2014	5 095,169	275,139	142,665
2015	5 347,562	304,811	144,384

Source: OECD/UNESCO/SA R&D Survey 2015/16

C1.2 Outputs: Patents and Publications

	Overall		Biotechnology		Nanotechnology	
	Publications	Patents	Publications	Patents	Publications	Patents
2005	4 676	463	62	10	205	10
2006	5 358	468	64	9	168	9
2007	6 016	470	83	7	195	16
2008	6 805	440	122	7	204	23
2009	7 578	338	163	9	218	20
2010	8 247	371	238	14	202	11
2011	9 596	371	282	14	267	14
2012	10 154	385	344	9	281	8
2013	10 986	325	257	9	271	15
2014	12 284	324	524	7	290	20
2015	13 063	302	620	5	315	13

Source: Patentscope & Clarivate Analytics

C2.The inputs and output data for the BRICS countries

C2.1 Inputs: R&D Expenditures US$ PPP Million

	South Africa	Brazil	Russia	India	China
2006	4 582,5	21 672,4	22 893,9	29 393,3	105 564,5
2007	4 872,3	25 829,0	26 535,7	33 527,5	124 199,2
2008	5 157,1	28 896,8	30 058,4	37 773,5	146 114,0
2009	4 813,7	28 812,2	34 654,6	40 194,7	185 300,8
2010	4 428,3	32 516,7	33 093,5	43 674,8	213 485,7
2011	4 652,2	33 904,4	35 192,1	48 063,0	247 808,3
2012	4 836,7	34 836,8	37 911,5		292 196,4
2013	4 956,7	38 733,3	36 614,1		334 116,6
2014	5 095,2	38 447,9	39 863,0		370 589,8
2015	5 347,6		40 522,1		409 576,9

Source: OECD/UNESCO

C2.2 Outputs: Patents and Publications

	South Africa		Brazil		Russia		India		China	
	Patents	Publications	Patents	Publications	Patents	Publications	Patents	Publications	Patents	Publications
2005	463	4676	365	17030	690	24549	1347	24363	3824	66029
2006	468	5358	436	19111	782	23979	1507	27638	5323	79629
2007	470	6016	556	23624	780	25360	1709	32398	6488	89070
2008	440	6805	579	28603	716	27238	1753	37034	6828	102465
2009	338	7578	562	30883	814	28239	1882	39107	10160	118982
2010	371	8247	575	32858	934	27917	2366	43099	13362	132271
2011	371	9596	652	35563	1037	29161	2128	47156	15634	155707
2012	385	10154	602	37572	884	28377	1439	49070	16491	178859
2013	325	10986	519	39216	782	29561	1477	53808	19178	211404
2014	324	12284	516	40684	736	30772	1373	59030	21285	245308
2015	302	13063	473	42412	700	34937	1515	61152	27595	274103

Source: Clarivate Analytics and Patentscope