UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Emerging Technologies for Technological and Economic Catch-up: The Case of Nanotechnology in South Africa

Geoffrey Simate Simate

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

Johannesburg, 2020

ABSTRACT

In a speech “There is plenty of room at the bottom” by Feynman (1959) the concept of nanotechnology was born, though the term itself was coined by Taniguchi (1974) later. Today, the world is witnessing unpreceded technological changes via nanotechnology which have affected every industry. Nanotechnology-based technologies have primarily continued to create a multitude of new processes and products that have substantially advanced the quality of life globally.

In terms of objectives, firstly, this study sought to establish if South Africa is creating technological and economic capabilities for catch-up, in general, and in nanotechnology, in particular. Secondly, the study looked at whether nanotechnology-based technologies (i.e., water treatment and medical applications) have facilitated technological catch-up, and subsequently, economic catch-up in South Africa. Nanotechnology being an emerging technology is considered by many scholars that it can offer windows of opportunity which are able to allow latecomer nations to catch-up with the technologically and economically advanced states.

The objectives of the study were investigated through quantitative methods, and the study used secondary data from government and institutional policy documents to assess technological and economic capability creation in both general terms and in nanotechnology. The evidence from a critical analysis of the policy documents shows that South Africa has invested heavily in capability building institutions such as the national innovation system (NIS) so as to boost its technological and economic development.

The NIS is a key concept which represents a country’s collective efforts towards advancing innovation (Manzini, 2012). It is ideally the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies (Freeman, 1989). The six functions of the NIS and the four mechanisms for knowledge flow were considered as the capability building blocks for innovation in South Africa and thus were used to operationalise the NIS. The six functions of the NIS according to the OECD (1999) include (1) technology and innovation policy formulation (2) financing R&D (3) performing R&D (4) promotion of human resource development (5) technology diffusion; and (6) promotion of

technological entrepreneurship. The four mechanisms for knowledge flow include (1) joint industry activities, (2) public/private interactions, (3) technology diffusion, and (4) personnel mobility (OECD, 1997).

The study also used bibliometric information of scientific publications and patents as measures and/or indicators for knowledge generation and invention, and subsequently, technological catch-up. Ideally, scientific publications and patents provide information pertaining to the trajectory of the technology and the key areas of innovation that may be necessary for economic growth and economic development. Two nanotechnology-enabled fields, water treatment and medicine, were specifically studied. The two fields are believed to be enablers of the UN millennium development goals for developing nations. The BRICS countries together with the USA were analysed in the study. The USA was found to be way ahead of the other nations in the two fields in scientific publications, citations of the scientific articles and patents filed through WIPO during the 9 year period from 2010-2018. However, China surpassed the USA on a year-by-year basis in nanotechnology enabled water treatment processes and/or products after 2016. The rest of the BRICS nations were found to be far below the performance of the USA in the two fields in both a 9-year period and on a year-by-year basis.

An interesting observation of the study is that there were more patents in medical fields than in water treatment. This trend is attributed by some scholars to intensive R&D in pharmaceutical industries than in any other industry. It was also observed that firms and/or universities were significant patent applicants in both fields whilst there were fewer individual applicants particularly in medicine.

One significant capability building strategy that was accessed in the study is collaborations amongst the studied nations. There are many benefits of collaborative working relationships including enhancing the quality of work undertaken and many more other advantages. Both nano-based water treatment and nanomedicine results had strong evidence that showed that collaborations maximized scientific research publications. Surprisingly, the collaborative results in scientific publications for South Africa with other BRICS nations was very low despite having a number of MoUs that encouraged R&D collaborative programmes amongst themselves.

It was expected from the study to find that nanotechnology cuts across the boundaries of various traditional fields of study within water treatment and the medical field. This is a clear evidence that nanotechnology has an inherent capability to unlock new and diverse opportunities in various fields.

Sales and /or market data was used to represent the economic impact of nanotechnology related products and/or processes. Unfortunately, data on assessment of economic impact of nanotechnology enabled materials in water treatment and medicine is not easily available due to numerous obstacles including elements such as regulations, standards, health & safety issues and public perception. Therefore, this study only provided results of sales and/or market data for nanotechnology-enabled products and/or processes in general, and not necessarily water treatment and medical related nanotechnology-based products and/or processes. Compared to other BRICS nations such as Russia, India and China, the results showed that South Africa does not seem to use nanotechnology as a “window of opportunity” for catching-up economically despite significant investment in the field by the government. The USA is currently leading in the generation of revenue from nano-enabled materials (see **Table 4.21**).

Key words

Latecomer; Catch-up; Emerging technologies; Nanotechnology; Invention; Innovation; Diffusion; Economic growth; Economic development; Quantitative methods; Qualitative methods; Longitudinal research; Cross-sectional design strategy; Secondary data

DECLARATION

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

Signature: 

Geoffrey Simate Simate

Signed in Johannesburg on the 26th day of August 2020

DEDICATION

Dedicated to my mother Bo ma-Mwiya Mukatimui Mashela, who sadly died on 30 June 2015.

Thanks mum for telling me from my childhood that "sikolo ki mutomo wa bupilo"!

Ni itumezi shaa. Koozo!

ACKNOWLEDGEMENTS

"...No man is an island, entire of himself...'' (John Donne, 1572-1631). This work is a product of my own. However, a number of people helped me where I fell short of wisdom during the production of this excellent piece of work.

To start with, I wish to express my sincere gratitude to my supervisor, Dr Diran Soumonni, for two glorious persuasions. Firstly, for the topic on technological and economic catch-up using an emerging technology as a favourable opportunity (i.e., window of opportunity) for a developing (or a latecomer) nation. Secondly, for convincing me to include sales and/or market data as a measure of economic catch-up not only using 'second generation' innovation output indicators. The first aspect enabled me to understand why some countries are 'poor by choice'. The second aspect was critical, because innovations that do not solve problems of the society and generate revenue are worthless. Lastly, but not the least, I thank Dr Diran Soumonni for the inexhaustible direction, advice and support that he offered me of his own volition.

The course work part of the programme was challenging, but had a viable team of academics who made it interesting. The syndicate assignments were quite vigorous, and sometimes frustrating and thus would like to cherish the contributions of my team members – Ntebo, Alu, Sihle and Hazel. I also specially thank Dr Elias Matinde who followed my foot-steps to enrol for the course after me for the robust discussions on a number of topics pertaining to the whole Innovation Studies course and my research topic.

It is my desire to acknowledge and appreciate the unparalleled support of my entire family during the period of my studies. Ms Maryna van den Heever, the Research Support Manager of the Wits Engineering library, is greatly appreciated for showing me how to extract data from the Web of Science, and Mr Brian Mwewa is acknowledged for actually extracting the data. Dr Catherine Namono who always assisted me whenever I had difficulties with EndNote is also greatly cherished.

The financial backing provided by the University of the Witwatersrand Staff Bursary Scheme that contributed to the successful completion of my studies, both coursework and research work, is duly applauded.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ASHK .... Academy of Sciences of Hong Kong
BRICS .... Brazil, Russia, India, China and South Africa
CSTP........ Council for Science and Technology Policy
FDI .... Foreign Direct Investment
GDP .... Gross Domestic Product
GNI........ Gross National Income
GNP .... Gross National Product
HICs .... High Income Countries
ICT .... Information Communications and Technology
ISO .... International Organization for Standardization
IST........ Information Society Technologies
ITB........ Innovation and Technology Bureau
ITC .... Innovation and Technology Commission
LICs........ Low Income Countries
LMICs........ Lower Middle Income Countries
NIS .... National Innovation System
NNI .... National Nanotechnology Initiative
OBM .... Own Brand Manufacturing
ODM........ Original Design and Manufacturing
OECD........ Organisation for Economic Co-operation and Development
OEM .... Original Equipment and Manufacturing
PCT .... Patent Cooperation Treaty
PSET........ Post-School Education and Training
R&D........ Research and Development
S&T .... Science and Technology
UMICs .... Upper Middle Income Countries
WIPO........ World Intellectual Property Organization

CHAPTER 1: INTRODUCTION

1.1 Purpose of the study

Whether it is a reality or an outsized expectation, nanotechnology is considered to possess illimitable potential to make major and drastic changes to a wide range of industries (Bhattacharya, 2015; Simate et al., 2013). In fact, many countries have invested heavily in the technology with the intention of developing new unique materials and systems that could have a positive and practical influence on the economy and thus ensure global competitiveness and sustainability (Ezema, I. et al., 2014; Pouris et al., 2012; Sargent, 2008). Nanotechnology, as a field, is regarded as a general purpose technology (Graham & Iacopetta, 2014), and Bresnahan and Trajtenberg (1995) describe such technologies as enabling technologies that can be used to invigorate radical and/or significant changes in the capabilities of a technology and/or create new and unique chances instead of giving absolute complete and final solutions. Accordingly, Ouellette (2015a) states that “in addition to opening new markets and fostering economic growth, nanotechnology also has the potential to enhance social welfare by addressing global sustainability challenges”. Furthermore, a study by Salamanca-Buentello et al. (2005) pointed out that nanotechnology can help third world nations to realise the UN millennium development goals (see **Table *2.5***).

With regard to the objectives, firstly, the study will determine the extent to which South Africa is creating general capabilities for technological and economic catch-up. Secondly, the extent to which capacity has been created in nanotechnology to advance technology and economic wellbeing of South Africa will also be evaluated. The final, but principal purpose of this current study is to establish whether nanotechnology offers a window of opportunity for techno-economic catch-up in South Africa. In view of whether nanotechnology offers a window of opportunity for techno-economic catch-up in South Africa, the study will, particularly, focus on two application areas of nanotechnology – water treatment and medical applications. Moreover, these are amongst the areas of nanotechnology pinpointed by Salamanca-Buentello et al. (2005) that were likely to assist poorer nations attain the UN millennium development goals.

1.2 Context of the study

Countries are normally classified depending on their general status of the processes related to economic well-being or development (Jamison, 1991). However, "when it comes to classifying countries according to their level of development, there is no criterion (either grounded in theory or based on an objective benchmark) that is generally accepted" (Nielsen, 2011). Moreover, there are a number of metrics that are used to categorise states with respect to their economic status. For example, some of the various measures and indicators of economic development include gross domestic product (GDP), gross national product (GNP), gross national income (GNI), per capita income, level of industrialization of the state, amount of infrastructure widely distributed within the country, the standard of living of its people, and many others (Nadakavukaren, 2011; Nielsen, 2011; Surbhi, 2015; Vaggi, 2017). Nevertheless, the GNI per capita calculated by the World Bank is the widely used system of categorising nations, and this system groups countries into four classes: low income countries (LICs), lower middle income countries (LMICs), upper middle income countries (UMICs), and high income countries (HICs) (Alonso et al., 2014; Fantom et al., 2014; Fantom & Serajuddin, 2016; Vaggi, 2017).

It is the aspiration of every country to rise up economically and/or ascend the ladder of economic development (Sachs, 2006) and thus reduce the difference in productivity and income between the frontier countries and themselves (Lee, 2005; Mathews, 2006; Zhang et al., 2017). Accordingly, Harack (2010) states that "climbing the ladder of economic development means the accumulation of wealth per capita which generally leads to healthier, happier, and longer-lived people". Economists refer to the capability of a country to reduce the difference in productivity and income between itself and the frontier countries as "economic catch-up", in general (Fagerberg & Godinho, 2004; Lee et al., 2016; Lee & Ki, 2017; Lee & Malerba, 2018; Wang, 2007); and over the past decades there has been more research on economic catch-up of latecomers with Japan being quoted as an early and good model of the catch-up notion (Lee et al., 2016). According to Lee (2016) "the key to economic catch-up lies in specific technological strategies". Therefore, the interest of this study is mainly technological catch-up which is a starting point or an ingredient or a catalyst for economic catch-up. Technological catch-up is defined as the "process of generating technological innovations at a faster rate than that of industrialised economies"(Soumonni, 2014). Similarly, Sohn et al. (2009) describes technological catch-up as the narrowing of technological differences and/or gap between the leading firms and/or nations through faster technological knowledge acquisition (i.e., learning) by latecomers. In addition, Chen and Li-Hua (2011) states that "technological catch-up refers to the latecomers developing continuously and rapidly by imitating the forerunners and to finally catch-up or surpass the forerunners within a short period of time". The significance of the notion of technological catch-up is that many countries including Korea and Taiwan moved up the ladder from behind in the middle class status to the top as nations in the high income group of economies category, to a large extent, due to technological catch-up (Yusuf, 2012).

Numerous models have been developed that explain growth trajectories during technological catch-up. Two of such models that have been extensively studied are, (1) the flying geese, and (2) leapfrogging (Hayter & Edgington, 2004; Lin, 2012; Long, 2014). These models imply that a number of different patterns and/or stages exist along the path of technological development that can be followed by latecomers (Kim, 1980, 1997; Lee, 2005; Wu, 1992; Wu et al., 2009).

The flying geese model explains catching-up as a linear and cumulative technological trajectory (Sohn et al., 2009). Ideally, according to the flying geese model, Radelet and Sachs (1997) states that during the catch-up process, latecomer "countries gradually move up in technological development by following in the pattern of countries just ahead of them in the development process". Basically, the model describes a sequence of import, consumer goods production, capital goods production and export, coupled with technological sophistication, to explain how latecomers caught-up with the leading goose (Akamatsu, 1962; Long, 2014). A good example of an application of the flying geese model relates to the East Asian tigers who mainly followed three distinct stages in their path of technological development (Tidd & Bessant, 2014). In the 1960s, the countries followed the "original equipment manufacturing" (OEM) system (Tidd & Bessant, 2014). The OEM is a specific form of subcontracting where firms in a catching-up nation produce goods according to the specification that is based in a technologically advanced country (Hobday, 1994). The second stage is the "original design and manufacturing" (ODM) in which the latecomer firms learn to design and manufacture products which are specified and branded by a firm in a technologically advanced country for their customers. The last stage is the "own brand manufacturing" (OBM) where latecomer firms design, manufacture and market their own products under their own brand name and compete head-on with the leaders (e.g., Samsung) (Tidd & Bessant, 2014). It must be noted, however, that the order of stages varied from country to country. For example, the Korean firms mainly followed the stage of OEM, OBM and then ODM because most of the Korean firms conducted their business with their own brand from an early stage of their development as the final assemblers, but also outsourcing most of intermediate goods (Lee, 2005).

The leapfrogging model postulates that latecomers can skip an existing technological trajectory to a more advanced stage of development or even create new ones (Lee & Lim, 2001). The telecommunication industry is a good example of the leapfrogging model. For example according to Mu and Lee (2005), "in terms of the technological trajectory of telephone switches, China skipped analogue-based telephone switches, but leapfrogged into digital-based telephone switches technology". Another example in the telecommunication industry is the adoption of mobile phones (wireless) in Africa, without first going through the conventional landline (wired) regime (Batinge et al., 2017). In the energy sector, Batinge et al. (2017) states that "leapfrogging has involved jumping to renewable energy without experiencing the dominant energy source regime (fossil fuel), and jumping from the dominant mode of delivering electricity (centralised grid transmission and distribution) to decentralised electricity provision through mini-grids and stand-alone systems". A study by Chen and Li-Hua (2011) has also shown that many Chinese firms have also been involved in technological leapfrogging.

Other models that complement the flying geese and leapfrogging models have also been developed. For example, Kim (1997) suggested that the evolution of technological capabilities in latecomers followed a series of capability building processes from duplicative imitation to creative imitation to innovation. Duplicative imitation refers to the transfer of technology for the production of identical goods to those of the competitor whereas creative imitation includes an active participation at the process of production not only to copy existing products, but also to make improvements to the previous versions of the product or adapt it to new uses (Baradello & Salazzaro, 2012; Nani, 2016). In simple terms, innovation, which is part of capability building processes as hypothesized by Kim (1997), can be defined as a process of transforming ideas and new knowledge into new processes, products and services (Ramadani & Gerguri, 2011). Wu (1992) distinguishes innovation into exploitative and explorative innovation. March (1991) states that “exploration includes things captured by terms such as search, variation, risk taking, experimentation, play, flexibility, discovery, innovation. Exploitation includes such things as refinement, choice, production, efficiency, selection, implementation, execution”. In other words, explorative innovation implies breakthrough or disruptive innovation whereas exploitation implies incremental innovation (Enkel & Gassmann, 2010).

Besides the catch-up models, a number of opportunities exist that can stimulate catch-up by latecomer nations. In other words, there are several windows of opportunity that are available for possible entry or catch-up by latecomers (Lee & Ki, 2017; Lee & Malerba, 2017). Indeed, depending on their strategic responses which rely on preconditions such as learning processes, level of capabilities, organisation and catch-up strategies, latecomers may take advantage of the window of opportunity (Lee & Malerba, 2017; Vértesy, 2017). Kenton (2018) defines a window of opportunity as “a short time period during which a rare and desired action can be taken” and can apply to a variety of situations (Lee & Ki, 2017; Lee & Malerba, 2017; Vértesy, 2017).

Short-cycle technologies are one of the windows of opportunity (Lee, 2013; Soumonni, 2014). According to Lee et al. (2017), “short-cycle time of technology means that the life span of the knowledge lasts only a few years and after that the usage declines dramatically as it soon becomes outdated or of less use”. One of the advantages of shorter-cycle technologies is that the entry barriers for latecomers are minimised because there is less reliance on existing knowledge dominated by advanced countries (Lee et al., 2017). In fact, according to Soumonni (2014), “shorter-cycle technologies take advantage of changing techno-economic paradigms that are still novel to all players across the globe”. A study by Lee (2013) has shown that countries and firms that specialised in sectors with short-cycle times of technology have been successful in catching-up. Park and Lee (2006) also obtained similar results – catch-up was found to be successful in technological sectors with shorter-cycle times.

Emerging (or new) technologies also play an important role in the entire catching-up process (Gerschenkron, 1962; Niosi & Reid, 2007; Perez & Soete, 1988), and many researchers consider emerging technologies as windows of opportunity (Lee & Ki, 2017; Lee & Malerba, 2017; Vértesy, 2017). According to Zhang et al. (2017) “developing countries have opportunities to catch-up in emerging technologies since emerging technologies are new to every country”. In fact, emerging technologies provide a level playing field since technologically advanced nations are also developing competences in the technologies at the same time as less technologically advanced nations (Bhattacharya & Shilpa, 2011). In addition, emerging technologies are vital to firms in developing countries because they produce opportunities for firms to put systems in place that could make them viable and competitive (Mathews, 2006; Mytelka, 2004; Zhang et al., 2017).

It must be noted that a significant number of emerging technologies are available. For example, Pouris (2012) identified 40 emerging technologies and grouped them as follows: nanotechnologies; knowledge-based multifunctional materials; new production processes; information society technologies (IST); life-sciences, genomics and biotechnology for health and sustainable development, global change and ecosystem. Amongst the many emerging technologies, this study focuses on nanotechnology.

Nanotechnology is an emerging technology (Cozzens et al., 2013; Islam & Miyazaki, 2010; Soumonni, 2016) which encompasses materials, tools and devices having at least one dimension of about 1-100 nm (Khan et al., 2017; Khanna, 2016). In simple terms, it deals with the manipulation and use of materials at atomic and molecular levels (Cappy et al., 2002; Mansoori & Soelaiman, 2005; Salamanca-Buentello et al., 2005; Sastry et al., 2013). IWGN (2000) states that the “essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization”. Niosi and Reid (2007) describe it as an enabling technology that provides tools, materials and devices for further technological development.

As a result of a number of benefits, nanotechnology continues to be a vital area of research and innovation in both developed and developing countries. In fact, it is already addressing and providing solutions to key economic sectors such as materials and manufacturing, life sciences, ICT and electronics (Bhattacharya, Sujit et al., 2012). For developing countries, nanotechnology can provide solutions in areas of concern such as the environment, water purification, agriculture, energy and many other products (Bhattacharya, 2015; Bhattacharya & Bhati, 2011; Bhattacharya, Sujit et al., 2012; Salamanca-Buentello et al., 2005).

The first objective of the study is to determine the extent to which South Africa is creating capabilities, in general, for technological and economic catch-up with the developed world. Thereafter, the study will evaluate capacity building strategies in the field of nanotechnology for technological and economic catch-up, and most importantly, the final objective is whether nanotechnology is providing a 'critical window' for South Africa to catch-up with the developed world. With regard to the 'critical window' for technological and economic catch-up, the study will focus on two fields in which nanotechnology is applied – water treatment and medical applications. Moreover, these are amongst the areas of nanotechnology identified by Salamanca-Buentello et al. (2005) that are likely to help less affluent countries achieve the UN millennium development goals. In addition, water and health were also singled out in the national nanotechnology strategy in DST (2005) as amongst six areas in which nanotechnology can create real benefits for South Africa.

1.3 Problem statement and research questions

A review of literature shows that catch-up strategies of latecomers have been studied extensively. Such studies have shown how latecomers have transformed their capabilities from being based on imitation to full-fledged innovation (Collins, 2015; Glass, 2010; Kim, 1997). For example, firms from China and other East Asian states have managed to catch-up, firstly, by learning and improving existing technologies through imitation (Glass, 2010), and secondly, the firms have grown significantly fast through endogenous innovation (Kim, 1997). Furthermore, recent research indicates that latecomers can also catch-up when a window of opportunity arises such as the appearance of a new emerging technology (Lee & Ki, 2017; Lee & Malerba, 2017). Emerging technologies are considered as key enabling technologies that could enhance industrial and innovation capacity and thus address societal challenges (de Almeida et al., 2013; Pouris, 2012).

Nanotechnology is a good example of an emerging technology in which many countries including South Africa have invested a lot with the aim of developing new materials and systems that could uplift their economies (Ezema, I. et al., 2014). Actually, there is a strong evidence that a number of developing countries such as Brazil, China, India and many others have been able to catch-up technologically using nanotechnology (Niosi & Reid, 2007; Salamanca-Buentello et al., 2005).

Unfortunately, there is little or no coherent evidence in literature that shows that South Africa is catching-up technologically and, possibly, economically using nanotechnology. Indeed, how South Africa could seize the opportunities in nanotechnology for technological and economic catch-up remains a poorly studied issue in literature. Therefore, this research seeks to determine the extent to which South Africa is creating capacity for technological and economic catch-up, in general, and in nanotechnology, in particular; and whether nanotechnology offers the window of opportunity for technological and economic catch-up in South Africa. The study focuses specifically on nanotechnology for water treatment and medical applications, and thus tries to ascertain the extent to which the two nanotechnology applications have advanced technological and economic catch-up in South Africa.

1.4 Significance of the study

The choice of the research topic emanates from the importance placed on emerging technologies globally. The emerging technologies present new growth opportunities to laggards for technological catch-up (Gerschenkron, 1962; Niosi & Reid, 2007; Perez & Soete, 1988). This particular study provides a deep understanding of the level of scientific and technological developments attained and subsequent economic achievements in the emerging technologies, particularly, nanotechnology for water treatment and nanotechnology applications associated to medicine, in South Africa, other BRICS nations and the USA.

Whilst many studies on nanotechnology in South Africa have concentrated on reviewing nanotechnology activities, no research has studied the extent to which nanotechnology-based technologies (e.g., water treatment and medical applications) have advanced technological and economic catch-up in South Africa. It is obvious that several catch-up studies have shown that technological catch-up is a pillar for economic development (Lee, 2016; Lee et al., 2016; Wang, 2007). Therefore, the results of this study will provide evidence to inspire South Africa to strengthen its industrial technological capabilities in the field of nanotechnology. There is no doubt that the development of industrial technological capabilities is an important factor for indigenous innovation (Long, 2014; Malerba & Nelson, 2011). Furthermore, nanotechnology based technologies have been lauded as having the potential to solve many of the problems faced by developing countries (Bhattacharya, 2015; Bhattacharya & Bhati, 2011; Cozzens et al., 2013; Salamanca-Buentello et al., 2005).

1.5 Delimitation of the study

(1) The study only looks at nanotechnology based technologies in water treatment and medical related fields in South Africa, USA and other BRICS nations and thus it may not be applicable to other nanotechnology areas studied in other countries or globally.

(2) The study uses secondary data (e.g., bibliometric information), and the results may be different if primary data was used.

1.6 Assumptions

(1) There is a linear relationship between (i) research and knowledge generation, (ii) knowledge generation and technological change, (iii) technological catch-up and innovation, and (iv) innovation and economic growth or economic development.

(2) The secondary data used in the study is reliable and/or valid based on the initial assumptions used in the primary data collection.

(3) The proxies for the NIS which include six functions and four mechanisms for knowledge flow give an accurate picture of the implementation of the NIS in South Africa (OECD, 1997; OECD, 1999).

1.7 Definitions of key terms

- **Latecomer firm**: According to Mathews (2002), "the latecomer firm is one which meets the four conditions:
  - *Industry entry*: The latecomer firm is a late entrant to an industry, not by choice, but by historical necessity;
  - *Resources*: The latecomer firm is initially resource-poor, e.g., lacking technology and market access;
  - *Strategic intent*: The latecomer firm is focused on catch-up as its primary goal;
  - *Competitive position*: The latecomer firm has some initial competitive advantages, such as low costs, which it can utilize to leverage its position in the industry of choice".

- **Catch-up**: According to Fagerberg and Godinho (2004) "catch-up relates to the ability of a single country to narrow the gap in productivity and income against a frontier country". Lee and Ki (2017) defines catch-up as "a substantial closing of the gap in market shares between the incumbents/leaders and entrants/latecomers".
- **Convergence**: In contrast to catch-up, "convergence relates to a trend towards a reduction of the overall differences in productivity and income in the world as a whole" (Fagerberg & Godinho, 2004).
- **Diffusion**: This refers to the dissemination of new ways on how to get things done through the various layers of production.
- **Emerging technology**: An emerging technology is defined by Rotolo et al. (2015) as "a radically novel and relatively fast growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and the patterns of interactions among them, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase it is still somewhat uncertain and ambiguous".
- **General purpose technology**: Bresnahan and Trajtenberg (1995) describes such technologies as enabling technologies that open up new opportunities rather than offering complete and final solutions. Nanotechnology is one of the examples of general purpose technologies (Graham & Iacopetta, 2014; Kreuchauff & Teichert, 2014; OECD, 2010; Shea et al., 2011; Soldatenko, A, 2011).
- **Nanotechnology**: Simate et al. (2013) describe nanotechnology as an emerging technology that "involves miniature, stronger, cheaper, lighter, durable, and faster devices with greater functionality and efficiency, apparently using fewer raw materials input and consuming less energy, but with very high productivity output".
- **Invention**: An invention is regarded as the generation of new ideas which are turned into technologies systematically. In other words, an invention is the creation of scientific ideas, theories or concepts that may subsequently result into an innovation when applied to a production process.

- **Innovation**: The OECD (2005) defines innovation as "the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations". Innovation may also be referred to as commercialization of invented ideas into marketable forms of products, processes or services.
- **Economic growth and development**: Economic growth, in general terms, refers to the increase in the GDP (or GNP or GNI) per capita (Colombatto, 2006; Haller, 2012). On the other hand, economic development is used in a broader context than economic growth. It encompasses processes and actions that generate improvements in people's economic, political and social wellbeing (Barkley & Barkley, 2013).
- **Secondary data**: According to Boslaugh (2007), secondary data refers to data that was collected by someone else for some other purpose. It is literally second-hand data (McCaston, 2005).
- **Quantitative methods**: According to Ashley and Boyd (2006), "quantitative methodology is associated with the rational and objective measurement of observable phenomena". In other words, quantitative research methods are characterised by the collection of information that can be analysed numerically, the results of which are typically presented using statistics, tables and graphs (ACAPS, 2013). According to Marshall (1996) and ACAPS (2013), the aim of the quantitative research method is to test pre-determined hypotheses and produce generalizable results.
- **Qualitative methods**: Unlike quantitative methods, "qualitative methodology focusses on assessment of subjective phenomena such as ideas, opinions, experiences and observed patterns" (Ashley & Boyd, 2006). In other words, qualitative data are often textual observations that portray attitudes, perceptions or intentions (ACAPS, 2013).

1.8 Research questions

The following questions arise for this study:

(1) To what extent has South Africa created capacity for technological and economic catch-up, in general, and in nanotechnology, in particular?

(2) To what extent have water treatment and medical related nanotechnology based processes and/or products advanced technological catch-up by South Africa relative to its BRICS counterparts and the technologically advanced USA?

(3) What is the extent to which water treatment and medical related nanotechnology based processes and/or products advanced economic catch-up by South Africa relative to its BRICS counterparts and the technologically advanced USA?

1.9 Structure of the research report

This research report is made up of six chapters including Chapter One that provides the context of the study and its motivation, a description of the problem statement, an outline of research questions, and the objectives of this study. The layout is schematically summarized in a flowchart in **Figure 1.1**.

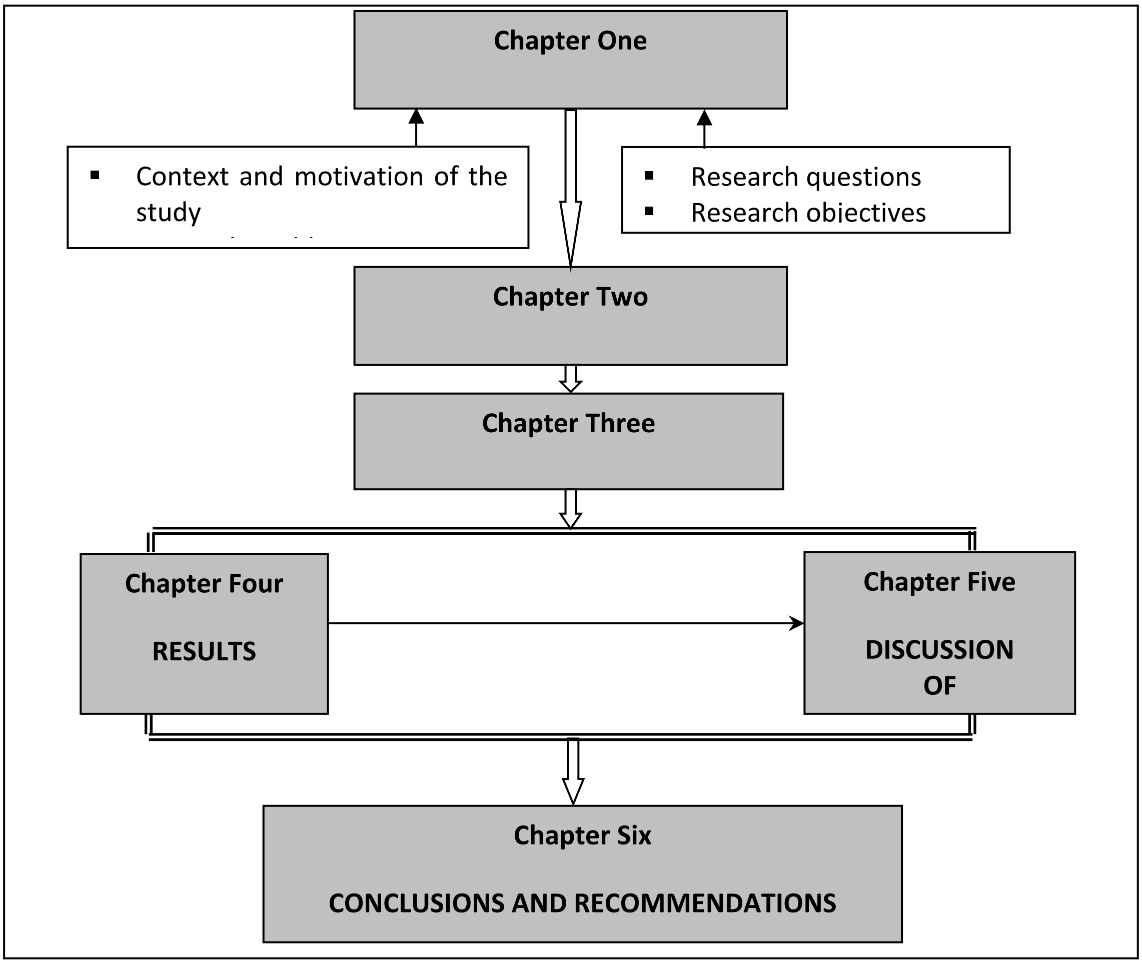

Figure 1.1. Research report layout

Chapter Two deals with the literature review, which includes the general knowledge of the classifications of nations based on economic development; the current models of catch-up and windows of opportunities such as the use of emerging technologies like nanotechnology. Chapter Three (research methods) describes the research strategies and techniques that are applied in the study. The subsequent chapters (Chapter Four through Five) describe the results and their discussions. The research report concludes in Chapter Six with a summary of the findings and recommendations.

1.10 Summary

This introduction Chapter laid a foundation of the whole study. It gave a background information about the subject under the study. The motivation of the study with respect to the research questions, its objectives and significance were outlined.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Over the years the difference in income (or productivity) per head between the rich and poor nations has been widening year-on-year. In his book, Landes (2015) acknowledges that the gap between the richest industrial nation and the poorest non-industrial country in the world today is over 400 to 1; yet more than two centuries ago the difference between the richest and poorest nations was about 5 to 1. Parente (2008) also agrees that a substantial difference in the living standards between the rich and the poor nations is a recent phenomenon. In this context, a number of studies have suggested that the economic growth of less developed nations is the solution to closing the gap between the rich and the poor countries (Wolla, 2017; Yifan, 2009). Fundamentally, the narrowing of the gap in income or productivity between a poor country and an economic leader is termed "economic catch-up" (Fagerberg & Godinho, 2004; Lee & Ki, 2017; Lee & Malerba, 2018). According to Lee (2016) "the key to economic catch-up lies in specific technological strategies". Therefore, this study mainly focuses on the technological catch-up as an ingredient to economic catch-up by South Africa using two nanotechnology based fields.

The scope and content of the literature review Chapter is organized as follows: Firstly, the Chapter gives an overview of what constitutes a poor or a rich nation, and some perspectives to why some countries are rich whilst others are poor. This is followed by a discussion of the notion of economic growth and economic development. Thereafter, the technological catch-up framework and innovation strategies for less developed nations as prerequisites for catch-up are then discussed. This includes catch-up models, required learning processes and capability strategies. Fourthly, the Chapter focuses on some windows of opportunity that are available for catch-up (see **Section 2.5**). Aspects pertaining to policy, in general, and innovation policy, in particular, are discussed in **Section 2.6**. The section also deals with innovation policies of selected nations. The principles that guide policy formulation for emerging technologies as stipulated by PCSBI (2010) are also discussed in **Section 2.6**. **Section 2.7** of the Chapter discusses the characteristics of nanotechnology as a general purpose and emerging technology. It also gives a brief overview of the top ten nanotechnologies that may assist developing nations to achieve some of UN's millennium development goals or even perhaps the most recent plan termed sustainable development goals; and the section also highlights how some countries have used nanotechnology as a window of opportunity to catch-up. The final section of the Chapter discusses the parameters used in the study for the measurements of technological catch-up and economic catch-up.

2.2 Poor and rich nations

In a day-to-day system of communication (or common language), the term ‘poor person’ refers to someone who has less income, wealth, goods, or services and vice-versa for a ‘rich person’ (Wolla, 2017). As for countries, they are normally classified according to their general level of economic development (see **Section 2.3** for the definition) and its effect on the average standard of living (Jamison, 1991; Whitfield, 2012) using a number of metrics. Some of the measurements used to assess economic development of a country include gross domestic product (GDP), gross national product (GNP), gross national income (GNI), per capita income, level of industrialisation, amount of widespread infrastructure, the standard of living, etc (Nadakavukaren, 2011; Nielsen, 2011; Surbhi, 2015; Vaggi, 2017).

The GDP refers to the total market value (in dollars) of all final goods and services produced in a country in a given year (Schmidt, 2019; Wolla, 2017). It is basically equal to all spending by government, consumer, and investments, plus the value of exports, minus the value of imports (Schmidt, 2019). It includes earnings made by foreigners living inside the country, but does not include earnings by its citizens living outside the country (Schmidt, 2019). Dividing a country’s GDP by its population gives its GDP per capita. This is an estimate of how much income (on average) the economy produces per person, and is a measure of the standard of living (Wolla, 2017). On the other hand, the GNI is GDP plus income paid into the country by other countries for things such as interest and dividends (minus similar payments paid out to other countries) (Schmidt, 2019).

In contrast to definitions of GDP and GNI, the GNP is the total market value of all goods and services produced by domestic residents (Schmidt, 2019). In other words, GNP includes domestic residents’ earnings from goods and services produced and sold abroad, and investments abroad, but does not include earnings by foreigners living inside the country (Schmidt, 2019). From the definitions of GDP, GNI and GNP, it shows that GDP and GNI refer to economic income generated within the borders of the country, while GNP refers to economic output by the country's residents (Schmidt, 2019).

For several years, GDP has been regarded by economists as the primary indicator of a country's economic output (Schmidt, 2019); and is basically used for identifying and measuring phases of the economy's business cycle, such as recession, depression, recovery, and expansion (Labonte, 2010; Schmidt, 2019). However, the GNI per capita calculated by the World Bank is the most widespread system of ranking and classifying countries, and this taxonomy classifies countries into four groups: low income countries (LICs), lower middle income countries (LMICs), upper middle income countries (UMICs), and high income countries (HICs) (Alonso et al., 2014; Fantom et al., 2014; Fantom & Serajuddin, 2016; Vaggi, 2017). According to Alonso et al. (2014), “GNI per capita is considered to be the best broad measure of a country’s economic capacity partly because other variables related to development achievements (such as infant mortality, literacy or poverty) seem to be highly correlated to GNI per capita”.

The World Bank assigns the world's economies into the four income groups based on GNI per capita (in US$) calculated using the Atlas method (WorldBank, 2018). In this method, a country’s income (GNI per capita) is converted from its local currency (WorldBank, 2018). Each year on July 1, countries are reassigned to an income group based on the estimate of their GNI per capita for the previous calendar year. According to the WorldBank (2018), “for the current 2019 fiscal year, low-income economies are defined as those with a GNI per capita of $995 or less in 2017; lower middle-income economies are those with a GNI per capita between $996 and $3,895; upper middle-income economies are those with a GNI per capita between $3,896 and $12,055; high-income economies are those with a GNI per capita of $12,056 or more”. According to this classification, South Africa is an upper middle-income economy (WorldBank, 2018).

Why are some countries poor, and others rich? This is the most pertinent question that has been debated over the years by economists. It is a contentious question that does not seem to have simple answers and thus has attracted researchers from various theoretical and conceptual backgrounds (Fagerberg & Verspagen, 2007). One school of thought considers technology as one of the key factors (Solow, 1957) whilst the other group of researchers regard geography as a significant factor accounting for the differences in incomes and productivity (Gallup et al., 1999; Sachs et al., 2001). Other economists argue that institutions and culture are important for economic growth (Bentzen, 2011). However, these different perspectives are not necessarily opposing one another, but are complimentary to the question at hand (FRB, 2004). Nevertheless, whatever the reasons, it must be noted that every laggard yearns to climb the ladder of economic development (Sachs, 2006) and thus reduce the difference in productivity and income between themselves and the frontier countries (Lee, 2005; Mathews, 2006; Zhang et al., 2017).

2.3 Economic growth and economic development

Brown (2013) defines an economy as “a system by which people get living”. According to Rees (2015), an economy encompasses everything associated with the production, allocation, exchange, and consumption of valuable goods and services, including the behaviour of various agents engaged in economic activities. All economies are real phenomena, but different economies vary considerably in sophistication and organizational structure (Rees, 2015). This variation in the economies leads to the categorisation of nations as discussed in **Section 2.2**.

Two fundamental processes that have been debated for centuries that relate to the health of nation’s economy are economic growth and economic development (Haller, 2012). Economic growth, in general terms, refers to an increase of the GDP (or GNP or GNI) per capita (Colombatto, 2006; Haller, 2012). It is achieved through an efficient utilization of available resources and by increasing the capacity of production of a country (Haller, 2012). On the other hand, economic development is used in a broader context than economic growth. It encompasses processes and actions that generate improvements in people’s economic, political and social wellbeing (Barkley & Barkley, 2013). Whitfield (2012) defines economic development as “sustainable economic growth accompanied by significant structural change in production patterns and generalised improvement in living standards”.

As previously stated at the end of the last Section, it is every country’s aspiration to climb the ladder of economic development (Sachs, 2006) and thus narrow the gap in productivity and income between themselves and the economic leaders (Lee, 2005; Mathews, 2006; Zhang et al., 2017). According to Harack (2010), “climbing the ladder of economic development means the accumulation of wealth per capita, generally leading to healthier, happier, and longer-lived people". Economists refer to the ability of a country to narrow the gap in productivity and income between itself and the frontier countries as "economic catch-up", in general (Fagerberg & Godinho, 2004; Lee et al., 2016; Lee & Ki, 2017; Lee & Malerba, 2018; Wang, 2007). According to Lee (2016) "the key to economic catch-up lies in specific technological strategies". Therefore, the particular interest of this study is technological catch-up which is an ingredient or starting point or catalyst for economic catch-up. Soumonni (2014) defines technological catch-up as the "process of generating technological innovations at a faster rate than that of industrialised economies". Moreover, it is the differences in technology which explain the variations that exist in GDP per capita across countries (Solow, 1957; Taskin & Zaim, 1997).

The concept of technological catch-up and its framework including innovation strategies are discussed in **Section 2.4**.

2.4 Technological catch-up framework and innovation strategies

Section 2.2 discussed the classification of nations based on their GNI per capita. It also gave a preamble to why some countries are richer than others. Concepts of economic growth and economic development were analysed in **Section 2.3**. **Section 2.4** is an extension of the previous two sections and examines technological catch-up and innovation strategies by less developed nations as catalysts for economic catch-up.

Studies have shown that there is a possibility for a low-income country to catch-up with frontier nations. Primarily, the catch-up by low income countries depends on a number of factors including ability to develop its own innovation system, a country's economic structure, characteristics of the domestic market, integration into international markets, collaboration with foreign partners (or companies), and population density (Baković, 2010; Fagerberg & Verspagen, 2007; Lee & Lim, 2001). However, recent research has also shown that processes of technological catch-up by latecomers do not merely follow the path initiated by advanced countries (Lee & Lim, 2001), but a number of different stages exist along the path of technological development that can be followed by latecomers (Kim, 1980, 1997; Lee, 2005; Wu, 1992; Wu et al., 2009).

The flying geese and leapfrogging are two models that have been the subject of several debates to explain growth trajectories during technological development of laggards. These models are discussed in **Subsection 2.4.1** and **2.4.2**, respectively. It is also important to note that learning, active assimilation and absorption of technologies are key capability building mechanisms for technological and later on economic catch-up (Lee, 2019; Wu et al., 2006) and thus are critically analysed in **Subsection 2.4.3**. **Subsection 2.4.4** discusses the concept of national innovation system (NIS) which is a core conceptual framework whose fundamental function is to generate, diffuse and utilise technologies that have economic value (Kayal, 2008).

2.4.1 The flying geese

The flying geese model illustrates the patterns and/or stages in the levels of economic development in industrialising countries (Akamatsu, 1962). Radelet and Sachs (1997) state that the flying geese model is a “major doctrine of development strategy” and during the catch-up processes the latecomer “countries gradually move up in technological development by following in the patterns of countries just ahead of them in the development processes”.

Akamatsu (1962) explained the fundamental pattern of the flying geese model in four stages as follows: “At stage one, the country begins to import manufactured consumer goods. In stage two, domestic industry starts the production of previously imported manufactured consumer goods, while importing the capital goods to manufacture those consumer goods. At stage three, domestic industry starts to export the manufactured consumer goods. At stage four, the consumer goods industry completes catch up with the industry in developed countries. The export of the consumer goods starts to decline, and the capital goods used in production of the consumer goods are now exported”. Following an explanation by Akamatsu (1962) of the important stages of the flying geese model, there is no doubt the model shows a hierarchical pattern to describe how industrialisation spreads (Anbumozhi & Yao, 2017).

The East Asian “Tigers” (South Korea, Taiwan, Singapore, and Hong Kong) and many other nations with similar policies mainly followed the flying geese model with three distinct stages in their path of technological development, i.e., initiation, internalisation and generation (Akamatsu, 1962; Lee et al., 2015; Long, 2014). The stages are also referred to as (1) original equipment manufacturing (OEM), (2) own design and manufacturing (ODM), and (3) own brand manufacturing (OBM) (Lee et al., 2015; Tidd & Bessant, 2014). In the first stage, firms in latecomers acquire already developed technologies, and this stage can be considered as an effort to catch-up by following a pre-set path, or simply "path following" (Lee & Lim, 2001; Lee et al., 2015). During the internalization stage, the internal R&D efforts of the latecomer firms result in the improvement of existing products, and may also include the production of new products. Ideally, according to Lee et al. (2015), "successful firms move toward ODM by designing a few of the products they previously manufactured". In the third stage, firms that have successfully passed the second stage will be able to generate new technologies. In other words, latecomer firms attempt something new, such as developing their own products and selling them under their own brand (Lee et al., 2015).

Other scholars have also advanced similar concepts of technological catch-up as well as the transition towards innovation. For example, Lee and Lim (2001) argue that firms in the latecomers went through five levels of technological capabilities in their business, i.e., "started with the assembly production of imported parts (OEM), then developed low- to high-tech parts (ODM), and learned to design the existing products with some modification (ODM), and finally, reached the stage of the new product concept creation (OBM)". Accordingly, the different stages and/or levels imply that economic development is a continuous operational process which involves industrial and technological upgrading in which any country, regardless of its level of development, can succeed (Long, 2014). Basically, the flying geese model offers a generic view of industrial upgrading that can be measured in various ways (Lin, 2012; Long, 2014).

Other scholars such as Kim (1980) also introduced a three stage model for catch-up in developing countries, namely (1) implementation, assimilation, and improvement. Accordingly, Kim (1980) states that "initially established through the implementation of imported foreign technology, local firms in the industry then accumulated experience in product design and production operation which provided a basis for limited indigenous efforts for the assimilation of imported technology. Finally, increased market competition in local and international markets and increasing capability of local personnel together with assimilation of foreign technology, led to gradual improvement of foreign technology".

2.4.2 Leapfrogging model

In addition to the different stages along the path of technological development, different patterns of technological catch-up have also been identified (Lee, 2005; Lee & Lim, 2001), which is in contrast to the flying geese model (Long, 2014). This alternative model to the flying geese model is termed leapfrogging model and postulates that latecomers can skip existing technological trajectory to a more advanced stage of development or even create new ones (Lee & Lim, 2001). In this regard, Lee and Lim (2001) have proposed three patterns of technological catch-up based on the experience of Korean industries, namely path-following, path-creating and stage-skipping. Path refers to the trajectory of technologies and stage means the stages in the trajectories (Lee & Ki, 2017). It must also be noted that each path as proposed by Lee and Lim (2001) may consist of several stages.

The three strategies proposed by Lee and Lim (2001) can be explained as follows. Path-following is a more traditional pattern in which the companies in developing countries follow the same path as taken by the forerunners in the successive stages, but in a more efficient way (Lee & Lim, 2001; Liu, 2006). As a result, latecomer companies will complete the path in a shorter duration than the frontier firms. In a stage-skipping catch-up pattern, a latecomer firm skips some of the stages in the process and jumps to a more advanced stage of development, and thus, significantly saves time. Path-creating firms follow their own path of technological development in order to narrow the gap with the frontier firms (Lee & Lim, 2001; Liu, 2006). According to Lee and Lim (2001) path creation may occur when the latecomers turn to a new path after having followed the path of the forerunners in a number of stages. This shows that catch-up strategies are not separate and different from each other, but can be taken up sequentially (Lee et al., 2016). In other words, at the early stage, catch-up can proceed with a path-following stage that relies on low-end markets, but the latter stage may require leapfrogging (stage-skipping or path-creating) strategies (Lee et al., 2016).

2.4.3 Learning, active assimilation and absorption of technology as an innovation capability building mechanism for catch-up

Kim (1998) argues that all organisations are learning systems because as they develop, produce, and market products they continuously learn. However, in contrast to the traditional technological learning model, Wu et al. (2009) argues that “without considerable active assimilation and absorption, the latecomer firm would probably fall into a vicious circle of ‘import – lag behind – import again’. In addition, Freeman (1989) states that “the success of latecomers has undoubtedly been due to the absorption of technology from the most advanced countries and their own efforts to adopt, adapt, modify and master the corresponding technical know-how”. Malerba and Nelson (2011) also acknowledge that learning, knowledge accumulation and capability building are key elements for changing the economic system of the laggards. Through the international diffusion of knowledge and technology, Taskin and Zaim (1997) states that “low income countries have the opportunity to adopt techniques of the leader and hence catch-up with the higher productivity countries”. Other researchers such as Pack and Nelson (1999) also suggest that countries such as the four East Asian “Tigers” used the knowledge acquired through absorbing knowledge from abroad to learn how to innovate.

The concepts of learning, active assimilation and absorption of foreign technologies are also clearly articulated in the secondary innovation theoretical framework by Wu (1992). Secondary innovation gives a valuable analytical framework that helps to offer a better understanding of the micro-level systems of learning, innovation and capability building in developing countries (Wu et al., 2006). It is defined by Wu (1992) as “the specific innovation process especially in developing countries that begins with technology acquisition from developed countries and further develops along the acquired technologies’ existing trajectories within established technological paradigm, which is generated and dominated by the original innovation process”. Ideally, it implies an innovation process by which developing countries combine technologies adopted from developed countries with technologies and local developments that are in existence (Wu et al., 2006). Furthermore, Wu et al. (2006) states that “secondary innovation is a ‘learning’ and ‘understanding’ process from mastery of operation technology, to mastery of production technology and principle, to mastery of design technology and principle, and to capability of product/process improvements”. Indeed, some scholars have also argued that the ability of a poor country to catch up with the frontier nations does not only come from its capability to source investments, but also from its potential to absorb existing technologies and generate new ones (Fagerberg & Verspagen, 2007).

Other scholars such as Kim (1997) have suggested that technological capabilities that would lead to catch-up by latecomers such as South Africa, emanate, initially, from imitations and, later, from endogenous innovations. Actually, over the years several researchers have studied the relationship that exists between imitation, innovation and economic growth (Cerqueti et al., 2016; Collins, 2015; Glass, 2010). According to Glass (2010) and Collins (2015) imitation can serve as a catalyst that can stimulate firms from lagging countries to undertake innovation. This is because imitation of products and their embedded technologies helps firms from latecomers to acquire skills and/or create a knowledge base that would enable them to be innovative and subsequently create new technologies and products (Collins, 2015; Connolly, 2003; Connolly & Valderrama, 2005; Currie et al., 1999; Glass, 2010; Van Elkan, 1996). As literature on economic catch-up by latecomers has shown, imitation is one of the strategies that were taken by Korea, Singapore, Taiwan, Hong Kong, and more recently China in their bid for technological catch-up (Liu, 2006; Pack & Nelson, 1999; Wong, 1999; Wu et al., 2009).

2.4.4 National innovation systems as an innovation capability building process for catch-up

According to Kosacoff (2013), the process of economic growth in a country, in general, or firm, in particular, depends on the creation of technological capacities and competences as well as the establishment and strengthening of institutions. In this regard, Lee (2019) argues that cultivating firm-level capabilities, for example, does not only involve the firms, but also the sectors and national innovation systems (NIS) surrounding them. In particular, it is viewed by Iddris (2015) that a well-structured NIS has the potential to support the development of innovation capabilities. The role of a well-functioning NIS is also acknowledged by the UNFCCC (2015) that states that "a country's technological capabilities are determined in part by the effectiveness of its NIS".

In simple terms, NIS is a key concept which represents a country's collective efforts towards advancing innovation (Manzini, 2012). Golichenko (2016) notes that NIS covers all the main features of the innovation process, including social, political, organizational, and economical elements. Therefore, a developing country should formulate NIS so that it strategically drives the catch-up processes (Kayal, 2008).

Whilst there is no specific definition of NIS, most definitions as given in **Table 2.1** depict NIS as a complex web of interactions within the system that involves the flow of information and technology.

Table 2.1. Definitions of national innovation system

Definition Number	**Definition**	**Reference**
1	"… the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies"	(Freeman, 1989)
2	"… the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge ... and are either located within or rooted inside the borders of a nation state"	(Lundvall, 2010)
3	"… a set of institutions whose interactions determine the innovative performance ... of national firms"	(Nelson, 1993)
4	"… consists of national institutions with their incentive structures and level of competence, and it determines the speed of dissemination and direction of technological knowledge"	(Patel & Pavitt, 1994a, 1994b)
5	"… that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies"	(Metcalfe, 1995)
6	"… all important economic, social, political, organisational, institutional and other factors that influence the development, diffusion and use of innovations"	(Edquist, 2010)
7	"… all economic, political and other social institutions affecting learning, searching and exploring activities"	(Feinson, 2003)

According to Patel and Pavitt (1994a) and Kayal (2008), the NIS has a number of components. Carlsson and Stankiewicz (1991) identifies three main components of the NIS: actors, institutions, and networks which contribute to the generation, diffusion and utilisation of technology. This view implies that the NIS phenomena recognizes the importance of not only the creation of new technological and business opportunities, but also their usage (Pihlajamaa et al., 2013).

Pihlajamaa et al. (2013) describes the three main components of the NIS as follows: (1) actors: "include organizations such as firms, universities, financial institutions, governmental agencies, groups of organizations, or individuals, e.g., consumers, entrepreneurs, and scientists"; (2) institutions: "encompass the 'rules of the game' such as laws, technical standards, regulations, norms, routines, and shared expectations that guide and regulate interactions and relations between actors"; and (3) networks: "define how different actors are interrelated and can be either formal or informal".

The following are examples of some of the institutions and actors as described by Patel and Pavitt (1994a), but there is no doubt that the list does not include all the elements: "(1) governments and related agencies supporting innovation through regulation, standard setting, public private partnerships, and funding of basic research, (2) sectors and industries comprising of firms which generate commercial innovations through experimentation, R&D, and product improvement, (3) universities which conduct basic research and train a technical and scientific workforce, and (4) other public and private organisations that engage in education oriented activities".

According to Kayal (2008), "the main features of the NIS are the capabilities of the institutions and actors to generate, diffuse, and utilise technologies (physical artefacts as well as technical know-how) that have economic value". Ideally, the performance of the NIS largely depends on how the actors and institutions function and interact with each other to develop and apply innovative knowledge (Akpolat & Chang, 2008).

2.5 Windows of opportunity for catch-up

There are several windows of opportunity that are available for possible entry or catch-up by latecomers (Lee & Ki, 2017; Lee & Malerba, 2017). Indeed, depending on their strategic responses which rely on preconditions such as learning processes, level of capabilities, organisation and catch-up strategies, latecomers may take advantage of the window of opportunity (Lee & Malerba, 2017; Vértesy, 2017).

2.5.1 Short cycle time technologies

It is important to note from the start of this discussion that catching-up by less developed nations takes place in specific economic sectors (Malerba & Nelson, 2011). Malerba (2005) defines a sector as "a set of activities which are unified by some related product groups for a given or emerging demand and which share some basic knowledge". Within this perspective, Lee (2013) found that countries and firms that specialized in sectors with short cycle times of technology have been successful in catching-up. According to Lee et al. (2017), "short cycle time of technology means that the life span of the knowledge lasts only a few years and after that the usage declines dramatically as it soon becomes outdated or of less use". In other words, existing knowledge becomes obsolete fast (Lee et al., 2017). Park and Lee (2006) also obtained similar results – catch-up was found to be successful in technological sectors with shorter cycle times. The first advantage of shorter-cycle technologies is that the entry barriers for latecomers are minimised because there is less reliance on existing knowledge dominated by advanced countries (Lee et al., 2017). In fact, according to Soumonni (2014), "shorter-cycle technologies take advantage of changing techno-economic paradigm that are still novel to all players across the globe". The second advantage of short-cycle times is that, as the new technology arrives more frequently, it results in high growth potential (Lee et al., 2017). Lee and Malerba (2017) also argue that the evolution of a sectoral system can open several "windows" that prompt different "responses" from latecomers and incumbents, thereby resulting in changes in industrial leadership.

2.5.2 Market demand and public policy interventions

Two other windows of opportunity discussed by Lee and Malerba (2017) are, (1) a business cycle and/or abrupt changes in market demand, and (2) public policy interventions. The market demand window could mean a major shake-up in local demand or a new set of consumers. The public policy window implies, for example, the generation of different environments for incumbents and entrants through a range of regulations (e.g., tax rebates, subsidies, etc). The issue of public policy is very important and is discussed in more details in **Section 2.6**.

2.5.3 Emerging technologies

Other scholars of evolutionary economics have argued that emerging technologies also offer windows of opportunity which allow less developed countries to catch-up (Gerschenkron, 1962; Niosi & Reid, 2007; Perez & Soete, 1988). Undoubtedly, less developed countries that participate in the initial stages of a given emerging technology have a good chance of technological catch-up (Niosi & Reid, 2007). Perez and Soete (1988) also held a similar view and concluded that the best opportunity available to developing countries for catching-up lies at the introduction phase of the new product. In addition, Zhang et al. (2017) states that "developing countries have opportunities to catch-up in emerging technologies since emerging technologies are new to every country". Consequently, in terms of emerging techno-economic paradigm, many researchers have also observed that since every country or firm is a beginner, entry barriers tend to be low suggesting the possibility of leapfrogging by latecomers (Lee & Lim, 2001; Lee & Mathews, 2013; Perez, 1988).

It must be noted that there is no widely agreed definition of an emerging technology (Halaweh, 2013). However, Rotolo et al. (2015) defines an emerging technology as "a radically novel and relatively fast growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and the patterns of interactions among them, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase it is still somewhat uncertain and ambiguous". This definition is based on five characteristics or attributes of emerging technologies identified by Rotolo et al. (2015), namely, (1) radical novelty, (2) relatively fast growth, (3) coherence, (4) prominent impact, and (5) uncertainty and ambiguity. A number of other definitions and/or meanings of emerging technologies are also available in literature (Halaweh, 2013; Srinivasan, 2008; Stahl, 2011), but many of them are misleading (Halaweh, 2013).

Examples of emerging technologies include nanotechnology, synthetic biology, genetic engineering, artificial intelligence, alternative and renewable energy, near field communication, cloud computing, virtual reality, advanced robotics, driverless vehicles, 3-D printing, mobile internet, the internet of things, and many others (Halaweh, 2013; Manyika et al., 2013; Soumonni, 2016).

As discussed already, the phenomenon of emerging technologies is very important in the entire catching-up process, and thus it is paramount for developing countries to significantly invest in them. Amongst the many emerging technologies on the horizon, this study focuses on nanotechnology with the view of answering the following questions pertaining to South Africa.

(1) Does the South African government have strategies and/or innovation policy instruments pertaining to nanotechnology-based technologies?

(2) Do nanotechnology-based technologies offer a window of opportunity for South Africa to catch-up technologically and economically?

The next two sections (**2.6** and **2.7**) address the two questions in general terms. For example **Section 2.6** explores the importance of innovation policy (**2.6.1**) and gives an overview of innovation policy initiatives of a selected number of countries (2.6.2), whilst **Subsection 2.6.3** gives policies for emerging technologies. Nanotechnology, in general, but with special emphasis given to ten applications of nanotechnology for millennium development goals, is discussed in **Section 2.7**. The section also highlights how some countries have used nanotechnology as a window of opportunity to catch-up (**2.7.2**).

2.6 Policy

The rapid economic growth achieved by the "Asian tigers" over the years has generated significant amount of research and interest (Lee & Lim, 2001; Pack & Nelson, 1999). However, Amsden (1994) asks why the whole world is not experimenting with the East Asian model in order to develop. Unfortunately, many countries seem to have even fallen behind. Pérez (2001) and many other scholars attribute such differences in results to be partly due to specific policies applied in each case. There is no doubt that policy plays a significant role in the technology gap view of development, and Verspagen and Kaltenberg (2015) states that "it is seen as a decisive factor for whether countries are able to catch-up to the global economic frontier, or will fall behind". So what is a policy?

Depending on the context and meaning that is conveyed, there are a number of definitions and/or explanations for the term 'policy' (Maselesele, 2011). Bates and Eldredge (1980) define policy as "a statement that provides a guide for decision-making by members of the organisation charged with the responsibility of operating the organisation". Similarly, according to Maselesele (2011), "policy mean broad guidelines or statement of goals for a course of action that should be followed in an institution to address a particular problem or a set of problems in order to provide consistency in decision making". Appiah-Kubi (2015) defines policy as "a statement of intent for achieving an objective".

Most importantly, windows of opportunity may be opened through policies and/or institutional changes (Lee & Ki, 2017; Lee & Malerba, 2017). For example, Lee and Malerba (2017) states that “governments may intervene through the establishment of R&D programs that affect the learning process and the accumulation of capabilities of domestic firms or through the provision of subsidies, tax reduction, export support, regulations, and public standards. The catch-up perspective suggests that the government creates an asymmetric environment in which incumbent firms (often foreign) are in a disadvantageous position (in terms of taxation, entry restrictions or marketing restrictions) at least in the domestic market of a country. Asymmetries could result in advantages for latecomers who can offset initial cost disadvantages associated with the entry”.

Sub-section 2.6.1 that follows gives a brief overview of the innovation policy; and also outlines in **Table 2.2** some of the objectives of innovation that drive different policies in various categories of countries according to the OECD (2012). An overview of innovation policy initiatives of a selected number of nations is given in **Sub-section 2.6.2**. **Sub-section 2.6.3** specifically focusses on the policies for emerging technologies such as nanotechnology.

2.6.1 Innovation policy

The view that policy may have a role in supporting innovation has become widespread, and thus the term innovation policy has become commonly used (Edler & Fagerberg, 2017). Edler et al. (2013) defines innovation policy as a “public intervention to support the generation and diffusion of new products, processes or services”. This encompasses a broad array of programmes, policies, and initiatives. Depending on the perspectives of innovation (broad or narrow), three main types of innovation policy may be distinguished – mission-oriented, invention-oriented and system-oriented (Edler & Fagerberg, 2017). The aim of mission-oriented policies is to provide new and practical solutions to specific challenges that are on the political agenda. Invention-oriented policies are centred mainly on the R&D/invention phase, and do not consider the possible exploitation and diffusion of the invention to the market. Edler and Fagerberg (2017) state that “system-oriented policies focus on system-level features, such as the degree of interaction between different parts of the system; the extent to which some vital component of the system is in need of improvement; or the capabilities of the actors that take part within the system".

The choice of instruments (regulatory instruments; economic and financial instruments; and soft instruments) is also a crucial decision regarding the formulation of an innovation policy (Borrás & Edquist, 2013). Innovation policies and principles need to be formulated and applied in a manner that accommodates the prevailing conditions of a country (developed, emerging or developing) in order to support its innovation endeavours (OECD, 2012). Accordingly, Kraemer-Mbula and Wamae (2010) have noted that developed and emerging economies are mainly focused on the creation of knowledge through R&D, i.e., technological innovation. On the other hand, the laggards make use of existing knowledge to generate value in the marketplace, i.e., non-technological innovation (Kraemer-Mbula & Wamae, 2010). In addition, Kraemer-Mbula and Wamae (2010) state that "innovation in developing economies is a means of job creation, wealth creation, and economic growth".

Table 2.2 shows some of the differences in the objectives of innovation that drive different policies in various categories of countries. It can be seen from **Table 2.2** that countries at different stages of development vary in their capacity to innovate (i.e., create and use knowledge). This is shaped by various factors, which include the conditions that enable countries to access, absorb and create new technologies (EBRD, 2014). Ideally, the extent and form of innovation depends on the characteristics of the knowledge involved in the innovation, and the characteristics of the innovating nations (or firms) (Kemp & Weehuizen, 2005). Therefore, policies designed to support innovation need to take these individual circumstances into account, and this is what distinguishes innovation policy in various categories of countries (e.g., developing countries) from innovation policy in general. It is also noted that vertical innovation policies that need a high level of governance are not suitable for developing countries, but policies that support multiple sectors may help to enhance the general innovation capacity of developing nations (EBRD, 2014).

Table 2.2. Objectives and type of innovation in various categories of countries (OECD, 2012)

Country category	Mechanism/objective of innovation	Type/source of innovation and main agents involved
This category of countries comprises of low-income or developing nations as well as middle-income and emerging countries	The adoption of innovation requires some form of adaptation: It is necessary that innovations respond to specific 'local' conditions for better outcomes	•Engage in incremental innovation that is based on foreign and/or non-indigenous technologies and innovations •Agents: These could include universities and research institutes, leading private businesses, especially those with contacts to foreign businesses and markets
	Inclusive innovation: This is a necessity concept for or by middle - and low-income households if their welfare and access to business opportunities are to improve	•Engage in incremental innovation that is based on foreign technology and/or generate local or traditional knowledge 'out of necessity' • Engage in social innovation that is earmarked at introducing technical innovations in local communities •Agents: These could include private associations, small firms, public and NGOs that ate involved in disseminating knowledge via a number of channels including networks, private, and often large businesses
These countries are mainly in the middle-income category, but there are also numerous opportunities for low-income or developing nations	It is important to build innovation capacities that are vital for reaching the world technological frontier in a number of industries. This approach is particularly relevant in order to avoid 'middle-income traps'	• Engage in both incremental and radical innovation capability building strategies so as to compete with world innovators at the frontier • Agents: This approach requires full development of a whole range of the innovation systems which should involve the diasporas as a connector
	There is need to address social ills including health, environmental, and social challenges via global innovation endeavours and locally tailored efforts to address them	•This include major innovations and scientific research that is conducted in global partnerships, but also include marginal innovations to are aimed at addressing poor people's welfare •Agents: This involves public and private universities and research institutions that are connected to global networks ,but major private businesses operating in these sectors are also included
	Grow niche competencies, i.e., growing and/or exporting products and services in sectors where a nation has comparative advantage	• This involves strategic support of industrial development by applying incremental innovations based on using foreign innovations and technologies •Agents: This include public institutions that are used to address co-ordination challenges, but also private sector initiatives including foreign companies are also engaged
This category consist mainly the middle-income or emerging nations after initial progress on the dimensions indicated above	Move up the value ladder in the global value chains	•This involves incremental and radical innovation capability building so as to differentiate contributions •Agents: This include private sectors involvement with support from public agents, intermediaries; diasporas can play a central role, and large firms are equally important
	Maintain competitiveness in industries that are at the frontier even when the country is at the frontier already	• Innovation in this category is identical to the developed countries that are exposed to developments in the global market • Agents: This involves mainly the private sector that interacts with public research institutions and universities; global partnerships are often equally of relevance, and the role of large firms is important

2.6.2 Innovation policy initiatives of selected nations

This section highlights some of the policy initiatives that contributed to successful catch-up by some countries.

The success of "Asian Tigers" is partly attributed to specific preference in their science and technology policies for developing and deepening indigenous technologies (Wong & Goh, 2015); and over the years, there has been radical changes in their innovation policies so as to pursue technological upgrading and diversification (Fuller, 2009). In the case of South Korea, "its success in leapfrogging technology generations has been underscored by a pragmatic strategy of starting at the low end of the market in new product segments and continuously improving its product sophistication, using economies of scale to secure a competitive market share" (Gupta et al., 2013). At the start of its economic development path South Korea acquired foreign technology through imitation and technical agreements (Gupta et al., 2013). However, Eriksson (2005) states that "Korea's policies on foreign licenses were quite restrictive in the 1960s. In the case of manufacturing, general guidelines from 1968 gave priority to technology that promoted exports, developed intermediate products for capital goods industries, or brought diffusion effect to other sectors. The restrictive policy on licensing strengthened local licensees' bargaining power on generally available technologies, leading to lower prices for technologies than would otherwise have not been the case". As a result, such policies enabled the Koreans to maintain control over the industrial base, encouraged investment in R&D from an early stage, and increased the likelihood of positive domestic spill-overs (Gupta et al., 2013).

Like South Korea, Taiwan also relied on foreign technology imports at the outset of its economic development, and has followed a broadly similar path to that of South Korea, although there are some significant differences between the two economies (Eriksson, 2005). From the beginning of its economic development, Taiwan wanted to move away from a condition of little know-how, inadequate institutions, and an under-supply of trained scientists and engineers to that of a high-tech based economy (Eriksson, 2005; Lin, 1998). In order to catch-up with the technologically advanced nations, Taiwan embarked on a four component strategy, namely (1) building human resources, (2) acquiring technology from the more advanced countries, (3) creating science and technology capacities, and (4) converting research results into commercial products (Lin, 1998).

Singapore has made enormous changes to its economy since independence (van der Drift, 2014). In the early 1960s, Singapore developed a policy of locational competitiveness which is still characterising its current efforts in promoting Singapore into a knowledge economy (Ebner, 2004a, 2004b). In this policy, the interest of the government is to create an attractive location so as to enhance foreign direct investment (FDI). Popovici (2017) defines FDI as an inflow of capital, technology and knowledge. Popovici and Călin (2014) also state that “FDI inflows are searching for locations abundant in natural resources or in created resources, such as better infrastructure, an attractive business environment, qualified employees, etc”. Siebert (2000) also argues that countries compete with their taxes, their infrastructure and their institutional setups. In addition, the choice of a location is also influenced by the motivation of the investing firm such as resource-seeking, market seeking, efficiency-seeking or strategic asset seeking (Popovici & Călin, 2014). In this regard, Singapore uses its policy of locational competitiveness to provide institutional and infrastructural structures that attract and/or enhance FDI (Ebner, 2004a). Ideally, according to Ebner (2004b) the locational competitiveness policy is aimed at an adaptive harmonisation of the needs of international investors with local developmental objectives. Doubtlessly, Singapore, just like a firm, has integrated the advantages of its geographic location together with its available resources and capabilities to enhance its existing competitiveness and develop new competitive advantages (Szałucka, 2015). More recently, Singapore has put more emphasis on business innovation and the commercialization of R&D, including creating customized platforms to facilitate the integration of the capabilities of research institutions, companies, and public-sector agencies to deliver innovative solutions (Poh, 2016).

The development of innovation and technology in Hong Kong is relatively recent compared to the other East Asian nations, and the country hopes to catch-up by leveraging advanced experience on the Mainland China and globally (Jie, 2017). Recently, Hong Kong set-up two institutions – Innovation and Technology Bureau (ITB) and the Academy of Sciences of Hong Kong (ASHK) (Jie, 2017). The ITB is responsible for formulating comprehensive policies to guide the Innovation and Technology Commission (ITC) (Jie, 2017) which supports different innovation activities, ranging from R&D (the Innovation and Technology Fund), technology ventures (the Applied Research Fund), design (the DesignSmart Initiative), and patent application (the Patent Application Grant) (Fuller, 2009). On the other hand, the ASHK is responsible for (1) bringing together the scientific research from universities in Hong Kong, (2) public education of science and technology, (3) scientific research, (4) science popularisation, and (4) co-operation with industrial and commercial institutions (Jie, 2017).

Other countries that have successfully developed technological catch-up strategies and/or policies include China, Brazil, and India, to name just a few. These countries have been able to build institutional and infrastructural networks for the assimilation of technological innovations. Most of the strategies revolve around enhancing the science and technology system, increasing investments in science and technology system and R&D, increasing the number of scientists and engineers, establishing high-tech parks, encouraging venture capital investments, better protection of the intellectual property, development of an entrepreneurial culture, and the involvement in international alliances to enhance learning opportunities and promote bridging to gain access to market (Liu et al., 2011; Niosi & Reid, 2007).

2.6.3 Policies for emerging technologies

There is no doubt that emerging technologies based on nanotechnology, for example, have been shaping the future of some industries and transforming many others (de Almeida et al., 2015). Therefore, because of the importance of emerging technologies, it is vital for countries to develop technological policies so as to establish an environment that is open to the new technologies. For example, the USA through the Presidential Commission for the study of bioethical issues identified five principles that must guide policy development for synthetic biology and any other emerging technologies (PCSBI, 2010). **Table 2.3** gives an overview of the five principles.

Table 2.3. Principles for guiding policy development for emerging technologies (PCSBI, 2010)

Guiding principle	Comment
The principle of public beneficence	This principle of the policy includes the responsibilities of the society together with that of the government to advance any individual and institutional activities and/or practices. Such practices and/or activities may include, but not limited to, scientific and biomedical research, that have great prospects enhance the society's well-being. This principle of public beneficence demands that when pursuing the benefits and/or any rewards of an *emerging technology*, the society and any of its representatives must be observant of any perceived or real risks and harms associated with the emerging technology. In addition, the society and any of its representatives must be ready to revise any policies that try to go after potential rewards and/or benefits, but having insufficient care taken to avoid danger or mistakes.
The principle of responsible stewardship	This principle requires that members of the whole global community must all have a duty and/or act in such a way so as to protect those who are not able to represent themselves such as future generations to come and the current children including the environment in which future generations will either prosper or perish. This is the basis of sustainable development (Brundtland et al., 1987).
The principle governing intellectual freedom and responsibility	This principle argues that unless there is high real or perceived risk, there should be no restrictions in the pursuit of research for knowledge. Ideally, there should be no self-regulations or government intervention. However, the scientific community in all sectors of academia, private or government should always collaborate in order to assess and respond accordingly to any potential and/or known risks of *emerging technologies* as the technology evolves.
The principle of democratic deliberation	This principles requires that the questions surrounding *emerging technologies* should be assesses and discussed continuously using established free and fair channels (i.e., democratic deliberations). In this way, the government and the community can effectively collaborate and thus ensure that *emerging technologies* can proper without any misunderstanding or confusion coming from divergent views which at times, have thwarted many other valuable scientific endeavours.
The principle of fairness and justice	This principle requires that both government and the community must act responsibly. For example, the government should enact rules for distribution of risks and benefits in research activities, and that the community should also consider having processes for fair distribution of rewards and/or benefits and dangers.

Besides the five principles outlined in **Table 2.3**, Pihlajamaa et al. (2013) argues that innovation policy can never be fully technology neutral. Ideally, innovation policy requirements differ from industry to industry (Bergek et al., 2008; Hekkert et al., 2007; Pihlajamaa et al., 2013). In other words, different technologies and sectors have needs that should be addressed in the context of the particular industries (Pihlajamaa et al., 2013).

It is also noted that, more often, innovation policies are developed to support existing technologies and/or industries thus significantly stifling the development of new and emerging technologies (Pihlajamaa et al., 2013). Therefore, in addition to the general innovation policy measures (e.g., tax reliefs for R&D), technology-specific measures should be designed to create growth trajectories for emerging technologies (Pihlajamaa et al., 2013). Some of the measures that can support growth of emerging technologies include good educational system, high quality basic research, public R&D funding support, and good infrastructure (Pihlajamaa et al., 2013).

In view of the aforementioned, the following question arises: Does South Africa have specific innovation policy measures that are designed to create technological growth of emerging technologies based on nanotechnology? This question is addressed in **Subsection 4.2.2** of Chapter 4, and fully discussed in **Section 5.3** of Chapter 5.

2.7 Nanotechnology

2.7.1 Nanotechnology as general purpose and emerging technology

A number of definitions for nanotechnology are available in literature some of which are shown in **Table 2.4**. However, despite having different phrases in the definitions shown in **Table 2.4** and many others, OECD (2010) argues that three characteristics of nanotechnology are emphasized in the definitions. The first aspect is that nanotechnology encompasses materials or processes in the nanometre scale. Secondly, the technology involves the purposeful manipulation, control and handling of matter at nanometre scale. As a result, this excludes accidental nanotechnology that occurs naturally without any purposeful engineering. The third characteristic is of commercial importance because it considers nanotechnology as an enabler of novel or new industrial applications as well as technological innovations.

Table 2.4. Common definitions of nanotechnology from literature (CSTP, 2001; Dube & Ebrahim, 2017; ISO, 2005; Maghrebi et al., 2011; NNI, 2000; OECD, 2010; Salamanca-Buentello et al., 2005)

Definition Number	**Definition**
1	"The essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization. Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes due to their nanoscale size. The aim is to exploit these properties by gaining control of structures and devices at atomic, molecular, and supramolecular levels and to learn to efficiently manufacture and use these devices" (NNI, 2000)
2	"Generating new knowledge on interface and size-dependent phenomena; nanoscale control of material properties for new applications; integration of technologies at the nano-scale; self-assembling properties; nano-motors; machines and systems; methods and tools for characterisation and manipulation at nano dimensions; nano precision technologies in chemistry for the manufacture of basic materials and components; impact on human safety, health and the environment; metrology, monitoring and sensing, nomenclature and standards; exploration of new concepts and approaches for sectoral applications, including the integration and convergence of emerging technologies" (OECD, 2010)
3	"Nanotechnology is an interdisciplinary and comprehension science and technology field that encompasses IT, the environmental sciences, life sciences, materials sciences, etc. By manipulating atoms and molecules on a nano scale (1/1,000,000,000 m), the unique material properties in the nano world lead to novel discoveries that can be exploited to innovate technologies in other fields. Nanotechnology also provides new materials, devices, and innovative systems to fields in IT, biotechnology, medical science, etc" (CSTP, 2001)
4	"Understanding and control of matter and processes at the nanoscale, typically, but not exclusively, below 100 nanometres in one or more dimensions where the onset of size-dependent phenomena usually enables novel applications. Utilising the properties of nanoscale materials that differ from the properties of individual atoms, molecules, and bulk matter, to create improved materials, devices, and systems that exploit these new properties" (ISO, 2005)

5	“The term nanotechnology covers entities with a geometrical size of at least one functional component below 100 nanometres in one or more dimensions susceptible of making physical, chemical or biological effects available which are intrinsic to that size. It covers equipment and methods for controlled analysis, manipulation, processing, fabrication or measurement with a precision below 100 nanometres” (EPO, 2013).
6	“Nanotechnology is the study, design, creation, synthesis, manipulation, and application of functional materials, devices, and systems through control of matter at the nanometer scale (1–100 nanometers), that is, at the atomic and molecular levels, and the exploitation of novel phenomena and properties of matter at that scale” (Salamanca-Buentello et al., 2005)
7	“Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1–100 nm range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size” (Maghrebi et al., 2011)
8	“Nanotechnology is the targeted and controlled synthesis/manipulation of materials, structures, devices and systems with accuracy/feature size of approximately 1–100 nm and preferably 2–50 nm” (Maghrebi et al., 2011)
9	“Nanotechnology is the application of engineered structures in the nanometre-scale size range (often 100 nm or smaller, but also 1–1000 nm), which possess desirable properties, e.g. magnetic, optical, biochemical, or electronic properties, and are generally applied to the benefit of mankind”(Dube & Ebrahim, 2017)

In addition to the three characteristics, nanotechnology does not belong to a specific technology and thus may be termed as a general purpose technology (Graham & Iacopetta, 2014; Kreuchauff & Teichert, 2014; OECD, 2010; Shea et al., 2011; Soldatenko, A, 2011). Lipsey et al. (2005) and Elhanan (1998) outline three attributes of a general purpose technology. Firstly, it provides rapid and significant scope for improvements of existing technologies in economic terms. According to OECD (2010), this characteristic "reflects the performance of some of the functions of nanotechnology that are vital to the functioning of a large segment of existing or potential products and production systems". Secondly, it should have a wide range of uses in a number of areas and industries. This feature emphasizes the enabling and generic nature of general purpose technologies which supports its widespread adoption throughout industries and economies (OECD, 2010). The third aspect of a general purpose technology is that it should both generate, and depend on, the development of a range of complementary technologies or innovations.

Nanotechnology is also considered as an emerging technology (Cozzens et al., 2013; Islam & Miyazaki, 2010; Soumonni, 2016), and according to OECD (2010) "nanotechnology holds out the promise of strong economic potential and may also help to address global challenges such as those relating to climate change, affordable health care, access to clean water, energy and other resource constraints". Many other studies have also strongly emphasized that nanotechnology has found widespread applications in various areas including water treatment, medical, automobile, food and packaging, cosmetics and sunscreens, building and construction, electronics and computing, clothing and textile, personal care and health, etc (Nielsen, 2008; Salamanca-Buentello et al., 2005; Soldatenko, Alexandrina, 2011).

Of particular importance is that, for developing countries, nanotechnology can provide solutions in areas of concern such as the environment, water purification, agriculture, energy and many other vital fields (Bhattacharya, 2015; Bhattacharya & Bhati, 2011; Cozzens et al., 2013; Salamanca-Buentello et al., 2005). In other words, nanotechnology can provide sustainable development in many important areas of developing countries (Ahmadvand et al., 2018). For example, a study by Salamanca-Buentello et al. (2005) correlated the top ten applications of nanotechnology that are likely to benefit developing countries with the UN millennium development goals (MDGs). The results of the study by Salamanca-Buentello et al. (2005) are shown in **Table 2.5**.

2.7.2 Nanotechnology as a window of opportunity to catch-up

Many countries around the globe have instituted various nanotechnology initiatives and/or programmes so as to maximise its potential for socio-economic development (Kumar, 2014). For example, (1) national nanotechnology initiative (NNI) (USA), (2) national enabling technologies strategy (NETS) (Australia), (3) Iran nanotechnology initiative council (INIC) (Iran), (4) national science and technology programme for nanoscience and nanotechnology (Taiwan), (5) nanoscience and technology initiative (NSTI) (India), (6) South African Nanotechnology Initiative (SANi) which is a predecessor for national nanotechnology strategy (NNS), and (7) agency for science, technology and research (Singapore). However, the USA's NNI started in 2000 is the only programme in the world with the greatest extent of comprehensiveness in the fields of nanoscience and nanotechnology, and many other nations have based their programmes on it (Bhattacharya & Bhati, 2011; Kumar, 2014).

This subsection discusses how a selected number of developing countries have used nanotechnology-based emerging technologies as a favourable opportunity for techno-economic catch-up.

Table 2.5. The relationships of the top ten applications of nanotechnologies in developing countries with the millennium development goals (Salamanca-Buentello et al., 2005)

Rank	Applications	Examples	MDGIs
1	The conversion, production and storage of energy	"Novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials; photovoltaic cells and organic light-emitting devices based on quantum; dots; carbon nanotubes in composite film coatings for solar cells; nanocatalysts for hydrogen generation"	7
2	Intensifying the production of agricultural products	"Nanoporous zeolites for slow-release and efficient dosage of water and fertilizers for plants, and of nutrients and drugs for livestock; nanocapsules for herbicide delivery; nanosensors for soil quality and for plant health monitoring; nanomagnets for removal of soil contaminants"	1, 4, 5, 7
3	The treatment and remediation of water	"Nanomembranes for water purification, desalination, and detoxification; nanosensors for the detection of contaminants and pathogens; nanoporous zeolites, nanoporous polymers, and attapulgite clays for water purification; magnetic nanoparticles for water treatment and remediation; TiO_2 nanoparticles for the catalytic degradation of water pollutants"	1, 4, 5, 7
4	The diagnosis and screening of diseases	"Nanoliter systems (Lab-on-a-chip); nanosensor arrays based on carbon nanotubes; quantum dots for disease diagnosis; magnetic nanoparticles as nanosensors; antibody-dendrimer conjugates for diagnosis of HIV-1 and cancer; nanowire and nanobelt nanosensors for disease diagnosis; nanoparticles as medical image enhancers"	4, 5, 6
5	The systems for the delivery of drugs	"Nanocapsules, liposomes, dendrimers, buckyballs, nanobiomagnets, and attapulgite clays for slow and sustained drug release systems"	4, 5, 6
6	The processing and storage of food products	"Nanocomposites for plastic film coatings used in food packaging; antimicrobial nanoemulsions for applications in decontamination of food equipment, packaging, or food; nanotechnology-based antigen detecting biosensors for identification of pathogen contamination"	1, 4, 5
7	The remediation of air pollution	"TiO_2 nanoparticle-based photocatalytic degradation of air pollutants in self-cleaning systems; nanocatalysts for more efficient, cheaper, and better-controlled catalytic converters; nanosensors for detection of toxic materials and leaks; gas separation nanodevices"	4, 5, 7

8	The construction industry	"Nanomolecular structures to make asphalt and concrete more robust to water seepage; heat-resistant nanomaterials to block ultraviolet and infrared radiation; nanomaterials for cheaper and durable housing, surfaces, coatings, glues, concrete, and heat and light exclusion; self-cleaning surfaces (e.g., windows, mirrors, toilets) with bioactive coatings"	7
9	The monitoring of health	"Nanotubes and nanoparticles for glucose, CO_2, and cholesterol sensors and for in-situ monitoring of homeostasis"	4, 5, 6
10	The detection and control of vectors and pests	"Nanosensors for pest detection; nanoparticles for new pesticides, insecticides, and insect repellents"	4, 5, 6

MDGs: (1) get rid of utmost hunger and poverty; (4) minimise the mortality of children; (5) enhance the health of mothers; (6) fight malaria, HIV and AIDS, and many other malady; (7) guarantee the sustainability of the environmental

Certainly, though nanotechnology has been embraced by a number of underdeveloped nations with a view of catching-up technologically, the extent of achievements in the field differs amongst countries (Niosi & Reid, 2007). As for China, since the establishment of its national strategy for the promotion of nanotechnology, there has been significant investment in various sectors (e.g., basic R&D, human resources, etc) in the field (Huang & Wu, 2012). As a result, based on a number of performance indicators, China is certainly becoming an important global player and/or recognised as a world leader in nanotechnology (Bhattacharya & Bhati, 2011). However, its performance in product development and nanotechnology patenting at international level is not strong compared to its research (Bhattacharya & Bhati, 2011; Huang & Wu, 2012; Niosi & Reid, 2007) where it is leading in terms of publications (Bhattacharya, Sujit et al., 2012). Despite such a drawback, China is prominent in the production of a number of nanotechnology based products and equipment. For example, a number of achievements have been discussed by Bhattacharya and Bhati (2011) such as, (1) creation of the atomic force microscope (AFP), (2) manufacturing of the scanning tunnelling microscope (ATM), (3) creation of the world's smallest carbon nanotubes (CNTs), (4) creation of yarn out of CNTs, (5) discovery of super-plastic property of nanostructured copper, and (6) creation of multicomponent materials featuring a variety of porous structures which may be used in catalysis and filtration devices.

In India, nanotechnology has received special attention from its government since the nanoscience and technology initiative (NSTI) got under way in the 10th plan of 2002-2007 (Bhattacharya, Sujit et al., 2012; Bhattacharya & Shilpa, 2011; Kumar, 2014). Consequently, countless upstream and downstream capabilities (e.g., scientific, technological and regulatory) have been strengthened (Ramani et al., 2011). In terms of innovation indicators (publications, patents, etc), India's scientific publications in nanotechnology have been growing steadily since 2002 (Ramani et al., 2011); and India is second to China in BRICS. There is also an increase in patent filling both via the Patent Cooperation Treaty (PCT) (or international applications) and the Indian Patent Office (Bhattacharya & Shilpa, 2011). Furthermore, India has developed competitive nanotechnology-based products in a number of areas including sports, textiles, medicines, computers, biotechnology, energy, and many other consumer related products (Bhattacharya & Shilpa, 2011).

Iran started its pursuit to develop nanotechnology in 2001, and in 2003 the country established the Iran Nanotechnology Initiative Council (Ghazinoory & Farazkish, 2010; Gholizadeh et al., 2015; Guston, 2010; Sarkar & Beitollahi, 2009). Iran is ranked amongst the top ten for the number of published nanotechnology related research papers in the world (Mahmoudzadeh & Alborzi, 2017). Iran's main priority is the development and production of nanocomposites, and thus, a number of companies in the first stage of their operations (or start-up companies) have been setup that produce several nanocomposite materials such as nanocomposite powders, nanocomposite foams, nanoclays, nanocomposite polymers, antibacterial nanocomposites, and nanocatalysts (Ghazinoory & Farazkish, 2010).

In additions to the three countries (China, India and Iran) discussed, many other developing nations are also building capabilities and capacity in nanotechnology (Salamanca-Buentello et al., 2005). A number of strategies being used by the developing nations include, (1) creating human resource capabilities, (2) infrastructure development (e.g., R&D clusters, assistance for fundamental research, venture capital, etc), (3) product development and commercialisation (e.g., early patenting), (4) creating alliances (e.g., public-private partnership and/or academia-industry partnership), and (5) regulatory frameworks (Kumar, 2014; Niosi & Reid, 2007; Ramani et al., 2011). There is no doubt that some of these strategies would minimise barriers to entry that latecomers must get rid of if they are to catch-up in nanotechnology-based technologies. The four entry barriers (or costs) identified by Perez and Soete (1988) are, (1) minimal amount of fixed investment, (2) required scientific and technical knowledge, (3) appropriate skills and experience, and (4) location-specific advantages.

2.8 Measurements and indicators of technological catch-up and economic catch-up

Two of the many forms of economic catch-up that have received widespread attention in both developing and developed economies are technological catch-up and market catch-up (Lee & Lim, 2001). The two types are not identical, but are related to each other in many aspects. Fagerberg and Godinho (2004) give the definition of catch-up, in general, as the capacity of a nation to reduce the gap in productivity and income against a frontrunner. According to Long (2014) catch-up occurs when industry actors in less developed economies are able to advance from their own technological capabilities towards the technological capabilities that are owned by the global industry leaders. Furthermore, Lee and Malerba (2017) define it as a "process of closing the gap in global market shares between firms in leading countries and firms in latecomer countries". Other scholars also have closely related definitions for catch-up.

Despite various wordings in the definitions of catch-up, it is widely acknowledged by many economists that successful catch-up is associated with innovation (Fagerberg & Godinho, 2004; Soumonni, 2014). Indeed, there is no doubt that the ability of a nation and/or firm to innovate is an important ingredient for successful growth and performance immediately and in the future (Carayannis & Provance, 2008; Iddris, 2015). In fact, several studies in the past have strongly linked innovation to economic growth and development. For example, (1) Solow (1957) showed that technical change in the USA was accountable for 87.5% of an increase in the capacity of the economy to produce goods and services (i.e., economic growth), and thus incorporated innovation into the economic growth model; (2) Fabricant (1954) suggested that 90% of the increase in the country's economic output (i.e., output per capita) in the USA between 1871 and 1951 came from technical progress. Modern research has also shown that innovation is the main driver of economic growth and development (Adak, 2015; Bayarcelik & Taşel, 2012; Cancino et al., 2018; Coccia, 2018; Nicolaides, 2014; Ramadani et al., 2013; Scherer, 1986; Thapa, 2013), and that it has many benefits to firms (Ramadani & Gerguri, 2011).

Considering the relevance of the concept of innovation for catch-up in addition to its significance with respect to economic growth and economic development, innovation is used as a proxy for technological and economic catch-ups in this study. A lot has been written about innovation and thus the term itself has many different definitions in literature over time. The OECD (2005) considers innovation as "the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations". Similarly, Khayyat and Lee (2015) look at innovation as "any practice that is new to organizations, including equipment, products, services, processes, policies, and projects". From different explanations of the term innovation that have been availed by a number scholars, it is clear that innovation includes the generation of completely new forms of knowledge, besides the diffusion and/or dissemination of already available knowledge (Rogers, 1998).

In view of the various definitions of innovation, its measurements have also evolved over time. Moreover, innovation is an intuitive and creative process which makes it even more difficult to measure (Chobotová & Rylková, 2014). Other scholars such as Morris (2008) also argue that the measuring of innovation itself is problematic because innovation entails going and exploring the unknown. Nevertheless, the development of innovation metrics has evolved over four generations as shown in **Table 2.6** (Chobotová & Rylková, 2014; Rizk et al., 2018).

Table 2.6. Development of innovation indicators and/or metrics over the years (Chobotová & Rylková, 2014; Rizk et al., 2018).

Input indicators or first generation metrics (1950s-1960s)	Output indicators or second generation metrics (1970s-1980s)	Innovation indicators or third generation metrics (1990s)	Process indicators or fourth generation metrics (2000s)
• Research and development expenditure • Science and technology personnel • Capital expenditure • Technological intensity	• Patents filled or granted • Publications of research output • Products produced • Quality change	• Indexing • Surveys of innovation • Benchmarking of innovation capabilities	• Knowledge • Intangibles • Networks • Customer demand • Clusters • Techniques related to management • Risk/return • Dynamics of a system

The first of the generations of innovation metrics focussed on input indicators, i.e., resources that are put into the innovation processes. The second generation indicators are mainly intermediate outputs related to scientific and technological activities. According to Baucher et al. (2013) “output indicators, such as patents and publications, provide information on the trajectories of a technology and on key areas of innovation”. The third generation indicators provide more comprehensive approach relative to the first two and focuses on indexing, innovation surveys and benchmarking innovation capacity (Rizk et al., 2018). In the current and fourth generation, relevant inputs (e.g., knowledge, intangibles, system dynamics, demand and risk/return) that were not previously taken into consideration are included (Rizk et al., 2018).

In this study, technological catch-up is operationalised using scientific publications and patent statistics. According to Hullmann and Meyer (2003) publications of articles from research (as measures of scientific performance) and patents filled or granted (as measures for technological performance) are frequently recognised as metrics for quantitative methods in innovation research. Huang et al. (2011) considers research publications and patents generated as excellent confirmations of the outcomes of scientific and technological efforts. Similarly, Verbeek et al. (2002) states that bibliometric information (scientific research publications, patents generated and citations from the research publications and patents generated) constitute a generally acceptable output indicators and/or second generation metrics of scientific and technological activities. Despite being legal documents, patents generated are also considered as a series of documents that provide written evidence of the advances in technology (Huang et al., 2011). In addition, patents generated have often been used as a measure of the performance of innovation activities in a significant number of studies (Dutta & Weiss, 1997; Henderson & Cockburn, 1994; Katila, 2000). Certainly, bibliometric data constitute an effective technique for illustrating, comparing and evaluating research activities and potential of long-established sectors and new areas such as nanotechnology (Alencar et al., 2007; Hullmann & Meyer, 2003; Preschitschek & Bresser, 2010).

One of the advantages of bibliometric assessments is that the data obtained can be repeated, verified and is not dependent on the choice of experts and their opinions, which may vary as the choice of the participants fluctuates (Pouris et al., 2012). According to Pouris et al. (2012) the most important advantage of bibliometric information is that it allows different scientific disciplines and different countries to be compared amongst themselves.

A number of studies have tried to assess the economic impact of the nanotechnology-based products (Baucher et al., 2013; NationalResearchCouncil, 2014; Ouellette, 2015a). However, the main difficulty in such studies is defining nanotechnology-based products (Ouellette, 2015a). In addition, Baucher et al. (2013) also argues that “while operational definitions for nanotechnology are developed at national or regional levels, there are relatively few internationally agreed upon definitions or classifications for nanotechnology or its products and processes”. There is no doubt that internationally agreed upon definitions of nanotechnology are essential when assessing its economic impact (Baucher et al., 2013). Furthermore, Gressmann et al. (2018) also argues that the definition of nanomaterials (in general or specific) is important when carrying out a market study on nanomaterials. Baucher et al. (2013) also notes that economic impact of nanotechnology is the most useful for policy makers. Unfortunately, relevant high-quality and quantitative data pertaining to nanotechnology is difficult to collect and thus it is not readily available (Baucher et al., 2013).

Both direct (market share, growth of companies, new products, wealth creation) and indirect (welfare gains, consumer surplus) indicators are available for assessing the economic impact of nanotechnology (Baucher et al., 2013). In this study, economic catch-up will be operationalised using sales and/or market data. Moreover, amongst various metrics for assessing the impact of nanotechnology Ouellette (2015a) states that the one “of most interest is some measure of the social benefit of nanotechnology, and the most common proxy for social benefit is the economic market value”. Lee (2013) also argues that using sales to represent catch-up, in general, is logical because sales growth is closely related to market share.

2.9 Summary

This Chapter interrogated the concept of catch-up and discussed various prominent models that explain the technological and economic trajectories to economic growth and development by some of the laggards. The most prominent models and/or narratives linked to the concept of catch-up include innovation, flying geese model, leapfrogging model, learning, knowledge, active assimilation, technology diffusion and absorption.

The definition of NIS, its importance in the development of innovation capabilities and its various components (actors, institutions, and networks) were discussed. Several windows of opportunities that are available to latecomers for technological and economic catch-ups were highlighted. The importance of innovation policies together with other initiatives and their contribution to successful catch-up were illustrated using a selected number of countries such as South Korea, Taiwan, Singapore and Hong Kong.

The significance and/or applications of nanotechnology in various fields and its relevance as a window of opportunity for technological and economic catch-up was explored, particularly, its ability to provide solutions in areas of concern to developing countries (see **Table 2.5**).

Finally, the measurements and indictors of technological and economic catch-up were selected based on the association of the two concepts to innovation. In other words, innovation is used in this study as a proxy for technological and economic catch-up. Technological catch-up was operationalised by scientific research publications and patent filed through WIPO. On the other hand sales and/or market data was chosen for assessing the economic impact. It is also argued by some scholars that using sales to represent catch-up, in general, is logical because sales growth is closely related to market share. However, sales and/or market data is difficult to access partly because such information is proprietary and is in the hands of private businesses. Many other reasons are outlined in **Section 4.4** of **Chapter 4**.

CHAPTER 3: RESEARCH STRATEGY AND METHODOLOGY

3.1 Introduction

Approaches to research can be broadly classified as quantitative and qualitative methods (Ashley & Boyd, 2006; Creswell & Creswell, 2017; Fairbrother, 2014). According to Ashley and Boyd (2006), "quantitative methodology is associated with the rational and objective measurement of observable phenomena, while qualitative methodology focuses on assessment of subjective phenomena such as ideas, opinions, experiences and observed patterns". This Chapter discusses a number of approaches that were used to answer the questions in this study and covers the following aspects: research method and paradigm; research strategy and design, sample selection, data source, data collection and analysis. It also includes the limitations, validity and reliability of the study.

3.2 Research method and paradigm

The methodology for research depends on the type and nature of research subject (Tafreshi et al., 2013). This research looked at the extent at which South Africa has created capacity for technological and economic catch-up, in general, and in nanotechnology, in particular (through policy; infrastructure; human resources; regulatory framework, etc). The last objective was to assess how nanotechnology-based processes and/or products have advanced scientific/technological catch-up (through bibliometric information) and economic catch-up (through sales) in South Africa compared to the USA and other BRICS nations. The study mainly involved the collection of numeric variables and their analysis so as to make valid conclusions. Therefore, this study is underpinned by a quantitative research approach.

According to Creswell and Creswell (2017), quantitative research tests objective theories by examining relationships among variables. Consequently, the most important feature of a quantitative technique is that it produces numerical data that can be analysed statistically (Rahman, 2016).

Some of the advantages of quantitative approach include, cost effective, fast data collection, less time consuming, ease of analysis and testing of hypothesis, and findings are likely to be generalised (Alkhaldi, 2003; Altaher, 2010; Rahman, 2016).

Similarly, Johnson and Onwuegbuzie (2004) also acknowledge that quantitative research can be replicated and thus it can be generalised which makes it credible.

This study used bibliometric data (scientific publications and patents) as indicators for scientific/technological catch-up and sales/market data as an indicator of economic catch-up. Therefore, the activities and/or trends of these indicators with respect to the two areas of nanotechnology applications (i.e., water treatment and medicine) were quantified and analysed accordingly so as to assess scientific performance and/or technological catch-up including sales and/or market performance. As a result, a quantitative approach was used in this study so as to ascertain the measurable extent of technological catch-up and economic catch-up. According to Alkhaldi (2003) the method would also help in "determining the relationships between variables and establishing the reliability and generalisability of data".

3.3 Research strategy and design

This study evaluated the extent at which South Africa has created capacity for technological and economic catch-up, in general, and in nanotechnology, in particular (through policy; infrastructure; human resources; regulatory framework, etc). It further looked at how nanotechnology-based processes and/or products have advanced technological catch-up in South Africa compared to the USA and other BRICS nations (through bibliometric information). Finally, economic catch-up in nanotechnology based processes and/or products for South Africa compared to the USA and other BRICS nations was evaluated through sales/market performance data. A summary of the parameters studied and their measurements is given in **Table 3.1**.

Table 3.1. Parameters studied and their evaluations and/or units of measure

Parameter	**Evaluation and/unit of measure**
National Innovation System	technology and innovation policy formulation; financing R&D; performing R&D; promotion of human resource development; technology diffusion; and promotion of technological entrepreneurship; joint industry activities; public/private interactions; technology diffusion, and; personnel mobility.

Scientific performance	Research publications
Technological performance	Patents
Economic performance	Sales/market performance data

This study followed a quantitative research approach informed by a critical policy analysis of the South African science and technology strategies in general, and for nanotechnology, in particular. In addition, the study used a longitudinal design strategy except for sales and/or market data that used cross-sectional design strategy.

According to Clark et al. (2015) longitudinal research approach involves repetitive collection and analysis of data over time. More precisely, Ployhart and Vandenberg (2010) define longitudinal research as “research that involves the repeated collection of at least one data source at three or more points in time”. Likewise, Kalaian and Kasim (2011) state that the “purpose of longitudinal research studies is to gather and analyse quantitative data, qualitative data, or both, on growth, change, and development over time”. In addition, Clark et al. (2015) state that longitudinal research is suited for investigating phenomena that change over time. These definitions emphasize time as a factor of major importance in longitudinal data analysis (Van Ness et al., 2011).

One of the approaches of this study was to use secondary data from bibliometric sources so as to analyse the activities and/or trends of scientific publications and patents as indicators for technological catch-up over time and thus the research strategy and design is in line with Clark et al. (2015) and many other scholar’s definition and/or purpose of a longitudinal design strategy. Periodic reviews and reformulation of policies in strategic plans by the government, with the view of creating capacity in nanotechnology based technologies or general capacity building strategies for technological and economic catch-up, also supports the use of longitudinal design.

However, due to difficulties in accessing data, the analysis of economic catch-up through sales data and/or market performance, using secondary data as well, was carried out via the cross-sectional design strategy. The cross-sectional strategy is a study that gives a snapshot of a particular study group at a given point in time (Alexander et al., 2015; Levin, 2006). Furthermore, Wright (2018) states that “cross-sectional studies are used to study a phenomenon by taking a cross-section of it at one time and analysing that cross section carefully". These definitions for cross-sectional design supports the strategy used for sales and/or market data. However, due to the difficulty in obtaining sales and/or market data as discussed in Sections 2.8 and 0, the time period of each country (South Africa, USA and other BRICS nations) analysed may not be the same as others.

3.4 Selection of sample

Three types of information were required for this study. Firstly, information on government policies (or institutional research strategies) pertaining to the creation of capacity in nanotechnology and general capacity building strategies for technological and economic catch-up in South Africa. Secondly, data on scientific/technological performance of South Africa compared to the USA and other BRICS nations with respect to nanotechnology based technologies, namely, water treatment and medical related fields. Thirdly, information on market performance and/or sales with respect to nanotechnology based technologies, in general (see **Section 4.4** for details), for South Africa compared to the USA and other BRICS nations.

In view of the information required, government policies (or institutional research strategies) on general capacity building strategies for technological and economic catch-up or creation of capacity in nanotechnology was obtained from (1) department of science and technology, (2) department of higher education and training, (3) National Research Foundation (NRF), (4) Mintek, and various other government entities.

The information relating to scientific productivity data was obtained from the Science Citation Index (SCI) that is part of the Web of Science (WoS) core collection databases. The databases within Web of Science are maintained by Clarivate Analytics (Li et al., 2018; Hossain, 2020). However, the Web of Science was originally produced by the Institute for Scientific Information (ISI) (CIKD, 2020). According to Verbeek et al. (2002),SCI is the most important database for bibliometric analyses. Makhoba and Pouris (2017) also state that SCI include most of the predominant and authoritative journals and fundamental literature globally. In this study, the Web of Science platform was used to access the SCI. In fact, the Web of Science is the world's leading scientific citation search and analytical information platform (Li et al., 2018;

Hossain,2020). MEDLINE/PubMed which is the premier database for retrieving biomedical journal literature, and covers virtually all health-care disciplines (Krieger et al., 2016) was not used to assess the scientific productivity of nanotechnology-enabled medical application in this study. This is because the Web of Science already indexes MEDLINE (MUSM, 2020). In fact, Krieger et al. (2016) further state that Web of Science together with Scopus are the two large, multidisciplinary bibliographic citation databases which cover the journal literature in a broad array of scientific, medical, and social sciences journals, including the humanities. It must be noted, however, that the SCI as of early 2020 has merged with Science Citation Index (SCIE). According to Liang (2010), the difference between the two databases was that all journals of SCI were available in the SCIE database, but not all the journals of SCIE were found in SCI. The other difference pertained to the storage media. The SCI was only available on CD/DVD format whereas the SCIE is available online (Liang, 2010).

This study used patent data from Patents Cooperation Treaty (PCT) by the World Intellectual Property Organisation (WIPO) which incorporates various databases including the European Patent Office (EPO), PatBase, United States Patent and Trademark Office (USPTO), SciFinder Scholar^{TM}, OECD, and many others (Fankhauser et al., 2018; Hullmann & Meyer, 2003; Katila, 2000; OECD, 2019; Preschitschek & Bresser, 2010).

The data on sales and/or market performance was obtained from various sources including research papers and reports from organisations such as Lux Research (i.e., Flynn et al. (2013)) and UNESCO.

3.5 Data collection

This study used secondary data. According to Boslaugh (2007), secondary data refers to data that was collected by someone else for some other purpose. It is literally second-hand data (McCaston, 2005).

As already discussed in the previous section, the data used to show that there is creation of capacity in nanotechnology by the South Africa government or general capacity building strategies for technological and economic catch-up was obtained from government policy documents (and institutional strategies). The data on market performance was obtained from various sources including research papers and reports from organisations.

The third aspect of data collection involved bibliometric information. The importance of bibliometric indicators (e.g., published articles and patents) on scientific areas is very much depended on the quality of their description (or delineation) (Zitt & Bassecoulard, 2006). Consequently, the bibliometric delineation of published articles/patents is one of the vital tools for keeping track of scientific/technological trends, and nanotechnology which is the basis of this study is not an exception.

Maghrebi et al. (2011) state that "the cornerstone for any bibliometric quantification practice is to build up a lexical query (LQ) which is defined as a set of keywords/terms organized with suitable Boolean operators (e.g., OR, AND, NOT), in order to retrieve the desired articles/patents totally and exclusively". Accordingly, a number of researchers such as Porter et al. (2008) have refined search terms for nanotechnology. However, this study used a simplified methodology by Maghrebi et al. (2011). According to Makhoba and Pouris (2017), the methodology "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)" and thus the methodology by Maghrebi et al. (2011) is a very accurate technique for selecting nanotechnology articles.

This study specifically focuses on water and medical related areas. Therefore, the keywords to these fields were defined specifically as discussed in **Subsections 3.5.1** and **3.5.2**, but it must be noted that the same key words were used for the search of both scientific publication articles and patents.

3.5.1 Water treatment area

A study by Cozzens et al. (2013) included three sectors (water, energy and agri-food) that incorporated half of the nanotechnology-based applications identified by Salamanca-Buentello et al. (2005) (see **Table 2.5** in **Chapter 2**) that could benefit people in the developing countries.

In particular, the following keywords were used by Cozzens et al. (2013) to search for nanotechnology applications in the water sector, namely, "brackish water, desalination, drink, filtration, freshwater, freshwater pollution, groundwater, natural waters, pesticide remediation, reverse osmosis, saltwater, seawater, water pollution, water purification, water treatment”.

This study used the same keywords used by Cozzens et al. (2013) to search for scientific publications and patents in the water field related to nanotechnology in South Africa, USA and other BRICS nations.

The sales and/or market data using a cross-sectional research approach was obtained from various sources including research papers and reports from organisations such as Lux Research (i.e., Flynn et al. (2013)) and UNESCO.

3.5.2 Medical related area

In a study by Wong et al. (2007), nanotechnology patents were classified into four broad areas of commercial applications, namely, (1) instrumentation, (2) chemical processes and materials, (3) medical and biotechnology, and (4) nano-electronics. These classifications of the applications of nanotechnology by Wong et al. (2007) constitute generally recognised applications of the field of nanotechnology and also largely correspond to the standard industrial classification used by other researchers including Hullmann and Meyer (2003), Meyer (2000), Meyer (2001) and Holister (2002).

In a previous study, the following key words were used to search for the medical and biotechnology application areas: “drug delivery, drug, diagnostic, medical, medicine, biological, nanoemulsion, cosmetic, bio, pharma, nanoshell, nanopor, nanocapsule, toxicity, nucleic, nucleus, antibacterial, antimicrobial, DNA, therapeutic, cell, protein, skin, immun$ (to include immunogenic and immune, immunity), antigen, antibiotic, vaccine, intravenous, oral, intranasal, disease, disorder, implant, biomaterial, infection, topical, gene, genome, virus, vector, peptide, in-vivo” (Wong et al., 2007).

With minimal refinement, this study used the same key words to search for scientific publications and patents in the medical fields related to nanotechnology in South Africa, USA and other BRICS nations.

Just like the water treatment field, the sales and/or market data using a cross-sectional design was obtained from various sources including research papers and reports from organisations such as WIPO and UNESCO.

3.6 Data analysis

The most important task of every research study is to investigate the research questions and analyse the data so as to achieve the intended research outcomes. Therefore, this particular task of data analysis requires careful planning. This study followed a quantitative research approach, and thus the data was mainly analysed by means of quantitative techniques. The analysis evaluated the scientific and technological trajectories of South Africa compared to other BRICS countries and the USA as a frontier technological nation. Similarly, market performance of South Africa in terms of sales emanating from nanotechnology-based materials (in general; see **Section 4.4** for details) was compared to other BRICS countries and the USA.

The policy documents from various government departments and institutions was only critically reviewed to assess nanotechnology capability creation and any general capacity building strategies for technological and economic catch-up in South Africa.

3.7 Statistical analysis

Statistical analysis is the science of collecting data and uncovering patterns and trends (Glen, 2014). More specifically, statistical analysis is concerned with the organization and interpretation of data according to well-defined, systematic, and mathematical procedures and rules (DePoy and Gitlin, 2016). The term data refers to information collected to answer such research questions as, “How much?”, “How many?” “How long?” “How fast?” and “How related?”. There are three categories of analysis in the field of statistics: descriptive, inferential, and associational. This study by its nature used descriptive statistics form, which is the first level of statistical analysis and is used to reduce large sets of observations into more compact and interpretable forms (DePoy and Gitlin, 2016). Firstly, the study is not designed to test a specific theory. Therefore, other forms of statistical analysis such as inferential statistics, which are concerned with testing the significance of a relationship so as to generalise findings to the population from which the sample is drawn were not relevant to this study. Furthermore, in view of the fact that this study is seeking an understanding of whether nanotechnology is enabling South Africa to catch-up, descriptive statistics are more appropriate. Moreover, the development of knowledge proceeds incrementally such that the first wave of studies in any particular area will be descriptive and is designed to describe the characteristics of a phenomenon (DePoy and Gitlin, 2016). In other words, description is the first step of any analytical process and typically involves counting occurrences, proportions, or distributions of phenomena. **Table 4.1**, **Table 4.4**, **Table 4.5**, **Table 4.6**, **Table 4.10**, **Table 4.15** to **Table 4.20**, and **Figure 4.1** to **Figure 4.10** are examples of descriptive statistical analysis, because they deal with counting occurrences, proportions, or distributions of a phenomena.

Another descriptive statistic technique that was used in the study was correlational analysis. For example **Table 4.15** and **Table 4.18** and results in **Figure 4.1**, **Figure 4.2**, **Figure 4.6** and **Figure 4.7** and the subsequent discussions in Chapter 5 have shown that there is strong relationship between collaborations and scientific research publications in nanotechnology-enabled technologies in both water treatment and medical applications. Many other types of correlational analysis have been discussed in Chapter 5.

Other techniques within descriptive statistics that were not used because it was not necessary include measures of central tendency (mode, median, and mean), variances, and contingency tables.

3.8 Limitations of the study

First and foremost, the concept of catch-up is multifaceted which include policies, technical capabilities, learning processes, active assimilation, absorption, and many other aspects all of which have some influence on each other. This makes the study quite complex, and thus, it only interrogates a few of these aspects. Secondly, it is quite challenging to obtain secondary data that is scattered in a number of databases some of which were not accessible. A study by Cozzens et al. (2013) also cited a number of limitations. For example, some databases may not include all publications because of their bias towards English language, and sadly only journals mainly from the USA and Europe are included in most databases. The other limitation is that the study might have missed some scientific and technological outputs because no keyword search strategy provides perfect retrieval system. There is also a possibility of non-reported scientific and technological and economic outputs by individual researchers. In this study innovation was used as a proxy for technological catch-up (see **Section 2.8**), and according to Morris (2008) measuring innovation is problematic because innovation is concerned with venturing into unknown which presents a limitation in terms of the choice of metrics.

Sales and/or market data for quantifying economic impact of nanomaterials was also not readily available for various reasons discussed in **Sections 2.8** and **4.4**. Therefore, in view of all the limitations stated in this section the results of this study may not be adequate and comprehensive.

3.9 Ethical considerations

This study did not use people or animals. Therefore, it does not violate research ethics which is succinctly defined by Saunders et al. (2009) as the "researcher's appropriateness in terms of his or her behaviour regarding the rights of human beings affected by the work of the researcher". All the data obtained for the study will be filed and kept in a safe place or captured electronically in spreadsheets/word documents and stored on the personal computer which has an automatic back-up system. In summary, the contents of this study including its methods are sound and morally acceptable.

3.10 Reliability and validity

This study uses methods that are dependable and thus the results are expected to be consistent and repeatable – thus meeting the reliability test; which is defined as the accuracy or precision of a measuring instrument (Olckers, 2011). On the other hand, Olckers (2011) defines validity as "the extent to which an empirical measure accurately reflects the concept it is intended to measure". In particular, external validity is concerned with the generalisability of results. This study assumes that the secondary data used is reliable based on initial assumptions used in the primary data collection (see **Section 1.6**). Therefore, it is expected that the results of this study can be generalised thus fulfilling the external validity principle. The other type of design validity in quantitative research is internal validity which Page (2012) refers to as the degree to which variables have been thoroughly controlled or accounted for. Many scholars have tested the methods used in this study and thus it is expected that the usefulness, correctness and accuracy with respect to internal validity was adhered to in the study. Moreover, the literature review was extensively conducted so as to identify sound theories and concepts related to technological and economic catch-up and many other features of this study, thus enhancing the validity of the study.

3.11 Summary

This Chapter presented the research methods and/or approaches used in the study. The study used secondary data, and depending on the objective(s), the study mainly collected numeric variables. Therefore, this study followed a quantitative research approach.

With respect to the first two objectives, (i.e., creation of capacity in nanotechnology and general capacity building strategies for technological and economic catch-up in South Africa) the study used information from government policy documents (or institutional research strategies). Bibliometric information was used in the study to assess the scientific/technological performance of South Africa, USA, and other BRICS nations, and two nanotechnology-enabled fields, water treatment and medicine, were specifically studied. Sales and /or market data was used to represent the economic impact of nanotechnology related products and/or products, in general, instead of the two fields due to non-availability of data amongst many other reasons. In view of the difficulty in obtaining sales and/ market data as discussed in **Sections 2.8** and **4.4**, the time period of each studied country (USA and the BRICS nations) may not have been the same as others. Finally, the study used a longitudinal design strategy except for sales and/ market data that used cross-sectional design strategy.

CHAPTER 4: PRESENTATIONS OF FINDINGS AND DATA

4.1 Introduction

This chapter presents the findings of the current study in accordance with the research questions stated in **Chapter 1**. The chapter is structured as follows: **Section 4.2** gives a critical review of innovation capability building strategies, in general (see **Subsection 4.2.1**), and in the field of nanotechnology, in particular (see **Subsection 4.2.2**). In **Section 4.3**, the results of technological catch-up are given. Finally, the chapter ends with the findings of economic catch-up in **Section 4.4**. **Section 4.5** summarises the chapter.

4.2 Innovation capability building strategies

In **Chapter 2** of this research report, it is clear from the review of literature that innovation underpins both technological catch-up and economic catch-up. Innovation generates and encourages competitiveness at various levels of the economy namely, the firm level, national and regional levels (Zulu, 2018). However, without innovation capability building, there can be no effective catch-up. In other words, capability building is essential for successful accomplishment of catch-up as indicated by a number of studies (Iddris, 2015; King & Fransman, 1984; Lall, 1992). In addition, Fagerberg and Srholec (2008) also emphasizes that “countries that do not succeed in developing appropriate technological capabilities and other complementary factors should be expected to continue to lag behind”. In this context, capability is defined by Grant (1997) and Yang (2012) as the extent to which specific individual resources can carry out intended work and/or sets of activities. More specifically, innovation capability is defined by Yang (2012) as “the potential ability of an organization to position itself in an arena of modernism such as new product development, technology and other advancements that result in competitive advantages over its rivals”. Furthermore, Antonelli (1999) states that “the innovation capability of firms rests upon varying combinations of localized and generic knowledge”.

This section of **Chapter 4** starts by looking at the capability building blocks for innovation in South Africa. In particular, it focusses on the NIS (**Subsection 4.2.1**), followed by capability building strategies in nanotechnology (**Subsection 4.2.2**).

4.2.1 National innovation systems in South Africa

In South Africa, the NIS has existed since the late 19th century or earlier in the 20th century (Walwyn, 2006). It is acknowledged by a number of researchers that South Africa contributed significantly to the areas of knowledge and technology as far back as the early 20th century (Scerri, 2009; Walwyn, 2006). For example, at the beginning of the 20th century, South Africa transitioned from farming and mining to a period of industrialisation that was led by the state (Hart et al., 2013). It is also noted that during the apartheid period, particularly, from 1970s "there was an emerging national science and technology R&D system that remained under the control of the state, and the system was mainly focused on the minerals, energy and the military-industrial complexes. However, the system was extremely exclusionary when it came to integrating personnel, research institutes and the private sector" (Hart et al., 2013).

According to Walwyn (2006), the transformation of the NIS which had stagnated and/or isolated during the apartheid years began shortly after the democratic dispensation (or more specifically, 1996). Ideally, the NSI was redesigned "to provide the basis and impetus for the development of a framework that has the cohesion, synergy and purposefulness in the national science-technology-innovation nexus" (Bawa et al., 2013). As a result, South Africa now operates with a much more integrated, well-co-ordinated and better aligned NIS to national objectives (Kaplan, 2004). The latest extensive review of various aspects of the NIS happened in 2018 (DST, 2018a).

The whole innovation process and/or NIS is dependent on relationships and the interaction of various actors (OECD, 1997; Zulu, 2018). In previous years, the NIS in South Africa was solely made up of public sector institutions and some actors, namely "high-level institutions statutorily mandated to provide policy advice to government on innovation, or innovation-related functions, including the national advisory council on innovation (NACI), the council on higher education (CHE) and the national science and technology forum (NSTF); government ministries and departments; research and innovation agencies, including the national research foundation and the medical research council; and research-performers, including universities and science councils" (DST, 2012). However, following the review of various aspects of the NIS in 2018 a quadruple helix approach has been adopted in South Africa (DST, 2018a). Accordingly, DST (2018a) states that "the quadruple helix approach is grounded in the idea that innovation is the outcome of an interactive process involving government, academia/the research sector, the private sector and civil society, each contributing according to its institutional function in society".

With respect to governance structure, set of policies, number of performing institutions and funding agencies, and to a large extent the actual innovation itself, there is no doubt that the South African NIS has reached a relatively mature and developed stage compared to its counterparts in other countries in Africa (Walwyn, 2006).

There are a number of vital and/or essential functions that are considered within a NIS. As discussed in **Chapter 2**, it is noted by Kayal (2008) that the "function of an innovation system is to generate, diffuse and utilise technology". Edquist (2004) also states that "the main function of NIS is to develop and to diffuse innovations". More specifically, the OECD (1999) considers "technology and innovation policy formulation; financing R&D; performing R&D; promotion of human resource development; technology diffusion; and promotion of technological entrepreneurship" as functions of the NIS. In addition, the OECD (1997) also regards the following undertakings as the mechanisms for knowledge flow within the NIS, (1) joint industry activities, (2) public/private interactions, (3) technology diffusion, and (4) personnel mobility.

This study considers the six functions of the NIS and the four mechanisms for knowledge flow as exemplified by OECD (1997) to be the capability building blocks for innovation in South Africa, and thus were used to operationalise the NIS. In principle, they all contribute to the overall objective of the NIS: the development, diffusion and utilisation of innovations (Bergek et al., 2008; Pihlajamaa et al., 2013). These capability building activities are addressed extensively in the subheadings that follows.

Technology and innovation policy formulation

Immediately after the dawn of democracy, the government of South Africa has played a vital role in shaping the NIS, by setting innovation policies, ensuring a conducive environment and intervening whenever there is a need (ASSAf, 2013; DST, 2012, 2018a). According to Golichenko (2016), policies are formulated to (1) increase innovation activities, (2) expand the actions and/or processes that encourage diffusion of new products and services, and cooperation amongst firms and/or nations, and (3) develop science and focus its attention on solving or finding solutions to the country's innovative development. However, innovation policies must be reviewed frequently due to rapidly changing techno-economic environments and because in many instances, the full potential of innovation policies may not have been realised (DST, 2018a). Nevertheless, Rodrik (2007) also argues that a country's innovation policies should not just follow the dictates of globalisation, but a country's own economic realities.

In an effort to build innovation capabilities, South Africa has over the years developed specific policy initiatives and strategies (ASSAf, 2013). Most importantly, there is a shift from focusing mainly on science and technology to innovation, but, nowadays, aspects of importance including social, institutional and other non-technological factors such as adoption of technology, diffusion of transfer and transfer of technology are also being addressed (ASSAf, 2013); this is because science and technology on its own does not necessarily translate into innovation, or growth of the economy or employment creation in the country.

In view of the aforementioned, there is no doubt, however, that policy initiatives and strategies with regard to either science and technology or innovation are attributed to the technological and economic successes of many countries (Wong & Goh, 2015). In addition, according to Lee (2016) "the key to economic catch-up lies in specific technological strategies". This view is also supported by Solow (1957) who stated that "technological improvements are the foremost drivers of economic growth". In this regard, the following are some of the policies and strategies developed that can serve as the basis for technological and economic catch-up in the Republic of South Africa:

National research and development strategy. This is the most important strategic document associated with South Africa's NIS (Kaplan, 2004; Walwyn, 2006). This strategy was established in 2002 in view of several deficiencies in many areas that matter to the economic wellbeing of South Africa including the following aspects: funding of science, technology and innovation, development of human resources, decline in private sector R&D, IP leakages, and uncoordinated efforts by the government in science and technology (ASSAf, 2013; Kaplan, 2004). According to Walwyn (2006) and Kaplan (2004), the national research and development strategy has many functions and/or strategic initiatives, namely, "to promote innovation and new national technology missions (e.g., (1) biotechnology, information technology, (2) technology for advanced manufacturing, (3) technology for and from natural resource sectors, and (4) technology for poverty reduction); to improve and diversify human resources; to promote a new set of science missions (in areas in which South Africa has an obvious geographic advantage, such as astronomy, human palaeontology and biodiversity, as well as in areas in which South Africa has a clear knowledge advantage, such as indigenous knowledge and deep mining); and to create an effective government science and technology system".

National advisory council on innovation. This is a trustworthy advisory body to the minister of science and technology. It is mandated to react quickly and positively to national matters pertaining to science and technology and most importantly, innovation. According to NACI (2019), the mandate of the national advisory council on innovation includes "coordination and stimulation of the NIS; promotion of cooperation within the NIS; structuring, governance and coordination of the science and technology system; revision of the innovation policy; developing strategies for the promotion of all aspects of technological innovation; identification of R&D priorities; and funding of the science and technology system".

National biotechnology strategy. This strategy was adopted in 2001 (ASSAf, 2013; Cloete et al., 2006), and its main focus is to address issues about development of human resources, funding of research, legal and regulatory issues pertaining to biotechnology; it also tries to reduce the gap that normally exists between research outputs and commercialization activities (Cloete et al., 2006). From its inception, the government has created and setup a number of regional centres of innovation including the biotechnology regional innovation centre (Walwyn, 2006) and has established and implemented initiatives to uplift international cooperation that can stimulate internal growth of life science undertakings (Cloete et al., 2006).

National Nanotechnology Strategy. This strategy started not as top-down, but as a bottom-up endeavour by scientists in 2002 who set up a group (or network) that was termed the South African Nanotechnology Initiative (SANi) (Harsh et al., 2017). Thereafter, the South Africa's Department of Science and Technology approved the strategy in 2005 (DST, 2005). The strategy is mainly concerned with areas that are expected to benefit the country (DST, 2005; Saidi & Douglas, 2017). Accordingly, energy, health care, water, mining and minerals, chemical and bio-processing, and advanced materials and manufacturing are identified by the strategy as important areas where nanotechnology has more advantages and/or can create more benefits for South African society as a whole (DST, 2005).

The Ten-year Innovation Plan: 2008 – 2018. This plan was aimed at transforming South Africa into a knowledge-based economy, in which the generation and distribution of knowledge is meant to lead the economic growth of the country for eventual betterment of all fields of South African human endeavour (ASSAf, 2013; DST, 2010).

Other strategies: There are several other strategies including the "Accelerated and Shared Growth Initiative for South Africa; National Skills Development Strategy for South Africa; Open Source Software and Standards Strategy; Towards a Framework for the Monitoring and Evaluation of South African Higher Education; Advanced Manufacturing Technology Strategy; Indigenous Knowledge Systems Policy; Higher Education Qualifications Framework; Framework for Intellectual Property from Publicly Financed Research; Technology Transfer Strategy, The Hydrogen Economy Initiative, Advanced Metals Initiative; Gender Equity Strategy; The Integrated Manufacturing Strategy; A Framework for Competition, Competitiveness and Development, and many more other strategies that are being developed" (Walwyn, 2006).

Financing R&D

It is a known fact that there exists a strong link between research expenditure and the production of scientific knowledge (Rosenbloom et al., 2015; Sanyal & Varghese, 2006). In addition, several studies have also shown the presence of a high correlation between levels of economic growth and development, and investments in research and development (Nicolaides, 2014). Moreover, developed nations allocate more funds into R&D (Bozkurt, 2015). In fact, Nicolaides (2014) states that "nations such as the USA and China are at the zenith of the list of the world's premier economies because they allocate vast resources into fostering innovation". In this context, a number of studies have shown that R&D expenditure have been found to be statistically significant in enhancing innovation (Conte & Vivarelli, 2014). More specifically, Wu (2015) argues that "innovation drives economic growth, and R&D fuels innovation because the pursuit of R&D allow scientists and researchers to be at the forefront of discovering and developing new knowledge, techniques, and technologies".

Table 4.1 indicates the amount of funding research and development as a percentage of GDP from 2005-2017 by South Africa including other BRICS nations and United States.

Table 4.1. Expenditure in research and development (% of GDP) (WorldBank, 2019)

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
South Africa	0.86	0.90	0.88	0.89	0.84	0.74	0.73	0.73	0.72	0.77	0.80		
Brazil	1.00	0.99	1.08	1.13	1.12	1.16	1.14	1.13	1.20	1.27	1.28	1.27	
Russia	1.07	1.07	1.12	1.04	1.25	1.13	1.01	1.03	1.03	1.07	1.10	1.10	
India	0.84	0.82	0.82	0.87	0.84	0.82	0.83	-	-	-	0.62	-	
China	1.31	1.37	1.37	1.44	1.66	1.71	1.78	1.91	1.99	2.02	2.06	2.11	2.10
USA	2.51	2.55	2.63	2.77	2.82	2.74	2.77	2.69	2.72	2.74	2.74	2.74	-

Investment in R&D is highly influenced by the economic power of a country, in addition to the importance that the nation places on research (Radu, 2018). As can be seen from **Table 4.1**, the USA still leads the other countries in R&D spending.

In South Africa, there are several organisations that have been established by the government with the aim of financing R&D and innovation. **Table 4.2** gives an overview of some of the organisations involved in funding R&D and innovation in South Africa.

Table 4.2. Major organisations involved in funding R&D and innovation in South Africa (NACI, 2017)

Funding organisation	Description
National Research Foundation (NRF)	The NRF was setup in 1998 via the National Research Foundation Act (Act No. 23 of 1998). It is the largest South African research funding agency. It is involved in funding the following activities and/or programmes: (1) the innovation honours, master's and doctoral programmes, (2) the South African Research Chairs Initiative, (3) the incentive programmes for rated researchers, (4) competitive support – rated researchers, (5) Centres of Excellence, (6) Human resource development next-generation and emerging researchers, 7) scarce skills fund, (8) square kilometre array, (9) iThemba labs, and (10) national equipment programme
Water Research Commission (WRC)	The WRC was created through the Water Research Act, Act No. 34 of 1971. Its primary functions have traditionally been to fund and steer South Africa's water research agenda, and to disseminate and effectively communicate research findings. The WRC also supports human capacity and skills development, in addition to leading technology, product and industry development. The WRC receives its funding from three sources: the water research levy, leverage funding and other sources.
South African National Energy Development Institute (SANEDI)	The SANEDI is responsible doing research and other activities that are related to energy in South Africa.
South African Medical Research Council (SAMRC)	Improving the health and quality life of all South Africans is the SAMRC's mandate. In addition, it conducts research is based on the following six research programmes: (1) health promotion and disease prevention, (2) maternal, child and women's health, (3) HIV, AIDS, TB and other communicable diseases, (4) health systems strengthening, (5) public health innovation, and (6) biomedical research Research takes place in intramural and extramural units. Extramural research units are situated at higher education institutions and are supported by the SAMRC.
Technology Innovation Agency (TIA)	The TIA was established under the Technology Innovation Agency Act (Act No. 26 of 2008). The TIA's mandate is to allow and give support to technological innovation within the economy of South Africa. To achieve these goals, TIA supports higher education institutions, science councils, public entities and private research institutions to commercialise its research outputs.

Performing R&D

Searching for new ideas and knowledge is one of the paramount elements of the innovation process (Hartono, 2015), and research is an important aspect of idea and knowledge generation. Research is defined by Andrew and Pedersen (2011) as a "scientific, purposeful, systematic and rigorous method of collecting, analysing, and interpreting data objectively or subjectively about some characteristic in order to gain new knowledge or add to the existing knowledge". Accordingly, the knowledge from research can be transferred into practice to help create new processes, products, and services that can subsequently enhance economic growth and development (Nicolaides, 2014). In fact, significant amount of studies are available that illustrate how scientific knowledge from academic research leads to successful innovations and economic growth consequently (Veugelers, 2014). Furthermore, Khan and Khattak (2014) states that “research plays an important role in economic growth of a country through technological advancement and spill-over effects”. Rosenbloom et al. (2015) also agrees that advancement in the understanding of science (or knowledge) is a vital contributing factor to a nation’s economic growth.

In the Republic of South Africa, the government is at the forefront of providing an enabling or conducive environment and any relevant resources including leadership required for the execution of science, technology and innovation (DST, 2018b). As a result, all of South Africa’s 26 publicly owned universities are directly and actively involved in R&D. According to DHET (2019b), the research outputs from public higher education institutions has been on an upward trajectory over the past number of years. The DHET (2019b) also states that “universities are key to developing a nation. They set norms and standards that underpin a nation’s knowledge capital and are dominant producers of new knowledge, critiquing information and finding new local and global applications for existing knowledge”.

Table 4.3 shows a selected number of other publicly funded institutions that are vigorously engaged in R&D in South Africa. These institutions are involved in (1) developing the needed knowledge in chosen fields, and (2) identifying, adapting and adopting the required knowledge generated elsewhere for the purpose of solving important problems affecting South African society, promoting innovation and exploiting emerging opportunities (Scholes et al., 2008).

Table 4.3. Selected number of publicly funded institutions and their roles (DST, 2018b)

Institution	Roles
Council for Scientific and Industrial Research (CSIR)	This is a premier organisation with respect to research in science and technology whose role is to accelerate socio-economic prosperity in South Africa by researching, developing, localising and diffusing technologies.
Council for Mineral Technology (Mintek)	The mandate of Mintek is mainly the promotion of mineral technology through doing research and transferring of technology. In so doing it encourages the setting-up and growing of industries related to the areas of minerals and products derived therefrom.

South African National Energy Development Institute (SANEDI)	Its main function is to conduct energy related research.
South African Medical Research Council (SAMRC)	SAMRC's main role is to produce and disseminate new scientific findings and knowledge on health.
Human Sciences Research Council (HSRC)	The HSRC is responsible for doing basic and applied research related to human sciences. The HSRC also has the responsibility to collect and analyse or even publish research that is pertinent to south Africa or Africa or global developmental challenges
Academy of Science of South Africa (ASSAf)	ASSAf has the responsibility to produce evidence-based solutions to national problems. "ASSAf recognises and rewards excellence; promotes innovation and scholarly activity; provides effective, evidence-based scientific advice to government and other stakeholders; promotes public interest in and awareness of science and science education; and promotes national, regional and international linkages"(DST, 2018b).
South African National Space Agency (SANSA)	According to DST (2018b) "the mandate of SANSA is to promote the peaceful use of space; support the creation of an environment conducive to industrial development in space technology; foster research in space science, communications, navigation and space physics; advance scientific, engineering and technological competencies and capabilities through human capital development, outreach programmes and infrastructure development; and foster international cooperation in space-related activities".
Agricultural Research Council (ARC)	DST (2018b) states that "the ARC conducts fundamental and applied research with partners to generate knowledge, develop human capital, and foster innovation in agriculture by developing technology and disseminating information".
Water Research Commission (WRC)	"The WRC provides the country with applied knowledge and water-related innovation, by continuously translating needs into research ideas and, in turn, transferring research results and disseminating knowledge and new technology-based products and processes to end-users"(DST, 2018b).

In addition to the publicly-funded research institutions and universities, South Africa also has a few private sector players that have substantive and well-resourced R&D capabilities, and hundreds of agile, low-overhead technical entrepreneurs (Scholes et al., 2008).

Promotion of the development of human resource

Human resources (or employees) are the valuable assets of any organisation (IBM, 2010). According to Gidhwani (2015), human resources are vital to the successfulness of any firm or organization because most of the problems pertaining to organizational settings are related to human and social challenges rather than failures in physical, technical or economical settings. In fact, Itika (2011) states that "evidence from economies in South East Asian countries suggests that the success behind these countries is largely explained by high investment in human capital". In addition, Walwyn (2006) also states that the necessary training given to human resources so as to drive innovation in a firm or country is a core requirement that is needed within any NIS. Moreover, human resources development (HRD) is extremely important in South Africa's technological and economic development agenda (DHET, 2009).

According to Nuffic (2015), there are three components of education system that are involved in human resource development in South Africa, namely, "General Education and Training (GET): Grade R up to and including Grade 9 which comprise the compulsory school-age years though grade R – the reception year – is not part of compulsory schooling; Further Education and Training (FET): Grade 10 up to and including grade 12 which comprise further academic schooling, as well as intermediate vocational education at technical colleges, community colleges and private colleges; and Higher Education and Training (HET)".

From the inception of democracy in South Africa, the country has made significant reforms to its higher education system (Ramrathan, 2016). Currently, there are 3 categories of higher education institutions, namely, "universities – these are the traditional academic universities that offer academic type degree programmes, including bachelor's, honours, master's and doctoral degree programmes, and are more focused on pure research; comprehensive universities – these are new in most cases and are a combination of the traditional academic universities and universities of technology, and; universities of technology – these are the old technikons which offer study programmes that are highly professionally oriented and a more practical focus" (DHET, 2019a; Nuffic, 2015).

At the moment, South Africa's major school-leaving qualification is the national senior certificate (Wedekind, 2013) and according to AfricaCheck (2019) and Wedekind (2013) four levels of achievements are possible: "a straight national senior certificate pass, or a national senior certificate pass with admission to a higher certificate, diploma or bachelor's degree". However, the only achievement that allows entry at a university by a pupil is the bachelor's degree. **Table 4.4** shows the number of pupils who wrote South Africa's national senior certificate exam and received a bachelor pass from 2008-2017, whereas **Table 4.5** gives figures that indicate the number of students enrolled in public institutions between 1994 and 2017. Some of the schools at these public institutions offer science, technology, engineering, and mathematics (STEM) subjects which play a key role in the sustained growth and stability of any country's economy, and are a critical component to helping a country win the future. The STEM education creates critical thinkers, increases science literacy, and enables the next generation of innovators.

Table 4.4. The number of pupils who wrote South Africa's national senior certificate examination and received a bachelor's pass from 2008 – 2017 (AfricaCheck, 2019).

Year	Number of pupils who sat for the examination	Number of pupils who obtained bachelor pass	% of the number of pupils who obtained bachelors pass
2008	554 664	106 047	19.1
2009	552 073	109 697	19.8
2010	537 543	126 371	23.5
2011	496 090	120 767	24.3
2012	511 152	136 047	26.6
2013	562 115	171 755	30.6
2014	532 860	150 752	28.3
2015	532 587	150 752	28.3
2016	610 178	162 374	26.6
2017	534 484	153 610	28.7

Table 4.5. Number of students who registered in public post-school education and training (PSET) institutions

Year	Type and number of institution*	Enrolments
1994	36 public universities and technikons	495 356
1999	152 TEVT colleges	357 885
1999	1 828 CET centres	294 855
2017	26 public universities	1 036 984
2017	50 TVET colleges	688 028
2017	CET Colleges	258 199

*TEVT = Technical Vocational Education and Training; CET = Community Education and Training

Table 4.6 shows the number of students who graduated with research related degrees (masters and PhD). It must be noted the numbers for master's degrees refer to the number of units for the research component of the degree. For example, the students who obtained their masters by pure research are given one unit and those who obtained theirs through 50% coursework and 50% research are given half a unit. All PhDs receive one unit because it is done through research. It must be noted that some of these institutions offer nanotechnology based research in water and medical fields.

Table 4.6. Number of masters (units) and PhD student graduations (DHET, 2016, 2017, 2018, 2019b)

Year	Number of units for masters degrees	Number of actual PhD degree graduates
2013	6411	2051
2014	7232	2258
2015	7317	2530
2016	7971	2782
2017	8011	3043

One important initiative by the South African government aimed at the development of human capital is termed the South African Research Chairs Initiative (SARChI). According to NRF (2018b) "SARChI aims to increase the scientific research and innovation capacity of the NIS by attracting and retaining established researchers that are considered global experts at local higher education institutions, science councils and national research facilities, respectively. The initiative attempts to build a critical mass of supervisory capacity, equipment, researchers and students around the research chair in support of domain-specific research where the domains are selected with consideration given to socio-economic needs as well as global research trends".

Technology diffusion

Various scholars have extensively studied and debated the process of technology diffusion for a long time (Jaffe, 2015). It is both a function of the NIS and a mechanism of disseminating knowledge within the NIS (OECD, 1997, 1999). Rao and Kishore (2010) consider the diffusion and/or spreading of an innovation (or technology) as a procedure or activity by which an innovation (or technology) is gradually passed through established channels among the members of an organisation or firm or nation. According to OECD (1997), technology diffusion is "the most traditional type of knowledge flow in the innovation system which many involve the dissemination of technology as a new equipment and machinery". In other words, "technology diffusion may be tracked through the sale of goods from one sector to another. In this way, purchased inputs act as carriers of technology across firms"(Stevens, 1997).

Table 4.7 shows technologies in the energy sector and the time scale required for deployment in South Africa. Cloete et al. (2014) states that the various green technologies in the energy sector given in **Table 4.7 "**were assessed from a global perspective in terms of their ability to lower the carbon footprint and their technology readiness level (TRL)”. The initiative showing very good chance of success for deployment within a short period of time was also identified, and any risks that could hinder progress in respect of technical and financial characteristics also formed part of the assessment criteria”.

Table 4.7. Various energy technologies showing technology readiness level and the time scale required for deployment in South Africa (Beck et al., 2013).

Technology	Technology readiness level	Timescale for wide deployment (years)	Most promising initiative for accelerating deployment
Hydro	9	Now	Design standardisation
Solar thermal	6-8	10+	Efficient thermal energy storage
Advanced solar photovoltaic	3-4	15+	
Photo (electro) chemical	1-3	10-15	
Geothermal	4-5	15+	Hot dry rock demonstration plants of > 50MW
Wave energy	4	15	High efficiency devices
Tidal current	5	15	High efficiency devices
Tidal barrage	9	5	High efficiency devices
Wind	9	Onshore: now Offshore: 5-10	Feed-in tariffs and commitments to technology deployment
Biomass	1st generation: 9 2nd generation: 5	1st generation: now 2nd generation: 5-8	Feed-in tariffs and commitments to technology deployment
Natural gas	9	Immediate	Natural gas from unconventional geological formations Fuel cells
Coal (including integrated gasification combined cycle (IGCC) and carbon capture(CC))	7	IGCC: 10 IGCC with CC: 20 Ultra super critical pulverised coal-fired (USCPC) with CC: 20	Carbon market and carbon emission constraints
Carbon sequestration	6	10+	Carbon market and carbon emission constraints
Nuclear energy	9	Generation II/ III: now Generation IV:15-25 Fusion: 35-50	Higher efficiency and improved safety

Key: TRL 1 = where the transition from scientific research is just beginning; TRL 9 = where the technology has been thoroughly tested and has been successful in the operational environment

Promotion of technological entrepreneurship

There is no general agreement of the exact meaning of the term entrepreneurship and what it means in practice such that numerous definitions have been given by various scholars in the recent past (Ayankoya, 2016; Sirelkhatim & Gangi, 2015). This study gives the meaning of entrepreneurship according to Kao (1993), namely, "entrepreneurship is the process of doing something new and something different for the purpose of creating wealth for the individual and adding value to society". Ayankoya (2016) considers entrepreneurship as the backbone of numerous flourishing economies globally. In addition, GEDI (2017) and Dejardin (2000) describe it as an impactful mechanism that drives economic growth, and Bubou et al. (2014) states that "entrepreneurship has been proven not only to be the impetus for growth and economic prosperity, but also serves as the foundation for the transformation of the modern economies".

Despite the importance of entrepreneurship, it is less effective in developing countries because of a number of reasons including inadequate training and education to entrepreneurs, non-availability of required financial capital, insufficient human resources with right skills and fewer sizable forms or organisations to help in the entrepreneurial exercise or process (Leitch & Harrison, 1999; Rogerson, 2008; Smit & Watkins, 2012; Wilkinson, 2017).**Table 4.8** gives an outline of the general strategies that are mainly required for furthering entrepreneurship in many countries around the globe including South Africa.

Table 4.8. General strategies for promoting entrepreneurship (Leitch & Harrison, 1999; Wilkinson, 2017)

Strategy	**Interpretation**
Literacy rates and human capital	This relates to the amount of knowledge possessed by entrepreneurs that they can use in a new business activity. When the skills and knowledge that the entrepreneurs have are superior, they are likely to achieve their goals and/or their new business will succeed since they are bringing in exceptional knowledge, more experience and special skills to the new business venture.
Educating and training toward entrepreneurship	This is the structured and targeted delivery of entrepreneurial capabilities and attributes. For example such capabilities and attributes purposefully offered to by the entrepreneurs could be in the form of new skills and advanced knowledge. As a result, the structured and targeted education and training of entrepreneurs can enable them to start, grow and be successful in their new business ventures.

Opportunity to obtain financial capital and raw materials	This refers to the fact that entrepreneurs should have opportunities to access finance and other materials vital at the time of starting-up and/or during the life time of their new business ventures. Such funds could help entrepreneurs with settling the costs of starting-up and other expenses that they may encounter as they grow and expand their businesses. Ideally, there are several avenues where finances could emanate, e.g., entrepreneurs' own funds or profit from their businesses or from external funders such as the government or other firms that may be larger and profitable.
Institutional support for entrepreneurs	Institutional support for entrepreneurs come in various forms. Such support may come from either the government or non-governmental institutions. Ideally, it comprises of authorities and institutions whose resolutions and person-centred approach in form of policies, laws, and regulation whether financial and non-financial help brings notable changes in the functioning of an entrepreneur's business.

Joint industry activities

According to Nibusinessinfo (2019), "collaboration is a powerful business tool for companies, regardless of their size or industry, and it typically refers to organisations working together to address problems and achieve goals that may be out of reach when working alone". A model developed many years ago argues that "science is most effective when researchers with expert knowledge in different areas collaborate on a project of overlapping interest. The overlap allows for common ground, while the respective areas of expertise cover a greater 'surface area' of the possible knowledge brought to bear on a specific question" (Sprunger, 2017). The OECD (1997) considers technical collaborations in addition to informal interactions amongst industries as one of the most significant ways in which knowledge is transmitted in the NIS. **Table 4.9** gives the nature of collaborations amongst some of South African companies. As can be seen from the table, collaborations in some firms also involve customers. In fact according to Yoon et al. (2017) "companies are increasingly cultivating collaborative relationships with a variety of external partners such as customers, suppliers and competitors to integrate value creation processes for sustainable growth".

Table 4.9. Examples of collaborations amongst South African companies

Companies	**Nature of collaborations**	**Reference**
Wine industry network of expertise and technology (Winetech), South African liquor brandowners association (SALBA), South African wine industry information and systems (SAWIS), Wines of South Africa (WOSA), and Vinpro	The companies created wine industry strategic exercise (WISE) as a collaborative initiative in 2015. The initiative's robust and adaptable approach is geared towards driving profitability, global competitiveness and sustainability amongst its members.	(WISE, 2017)
The supplier-buyer cooperation in textile industry in South African	This refers to a collaboration between suppliers and buyers within the textile industry which is concerned about the development of products	(Parker, 2007)
Woolworths, K9 pet foods and the Industrial Development Corporation (IDC)	K9 pet foods supplies Woolworths with pet foods as an import replacement strategy by Woolworths. The IDC financed K9 pet foods so as to expand its plant and also buy the most recent equipment which could help them achieve requirements for manufacturing of pet foods. The funds from IDC also stimulated and made it easier for K9 to specifically design an innovative technology for Woolworths.	(Woolworth, 2017)
South Africa's macadamia industry	Proactive industry body and government collaboration is integral to ensure the standard is set for macadamia industry's future.	(Aylward, 2019)
Automation industry	With the view of evaluating and seeking solutions to its challenges the automation industry is cooperating through a number of initiatives including the Africa Automation Fair and Connected Industries conference. The industry is also involved with security of information and the integration of their systems.	(Bizcommunity, 2018)
South African construction industry	With the objective of creating more value for its customers (i.e, lean principles) the industry is creating an amalgamated and customised approach. It is also getting rid of the segregated supply chain within the construction industry which prevents the generation and upgrading of value in the whole process of construction.	(Emuze & Smallwood, 2014)

Public/private interactions

It is well established by various scholars that collaboration between academic institutions and the industry is a vital aspect of the NIS (Guimón, 2013; Ndlovu, 2017;

Sá, 2015). Sprunger (2017) also argues that "working with others outside of your comfort zone can also provide you with novel skills, theories, and methods that enrich your research and make you a more unique, innovative, and marketable professional". The OECD (1997) regards public-private (or academic-industry) cooperation as a primary mode of knowledge flow in the NIS. Some studies in South Africa also indicate that academics, in generally, consider the interactivity with external industrial partners as advantageous or a correct feature of their duties (HESA, 2012). **Table 4.10** shows some typical outputs that have previously emanated from university-industry engagements.

Table 4.10. Outputs emanating from academic engagements with firms (HESA, 2012)

	SMMEs*	MNEs*	Large firms
Graduates with pertinent expertise and principles	963	691	930
Publications of academic nature	862	653	862
Dissertations (or thesis)	814	616	812
General reports, policy reports and any popular publications	766	576	756
Cultural objects and/or artefacts	263	183	243
Collaboration of academic nature	925	677	901
Spin-off firms	277	448	253
Infrastructure and facilities for the community	488	355	460
New and/or improved products	481	370	457
New and/or improved processes	682	520	671
Scientific findings and discoveries	428	344	433

*SMME= small, medium and micro enterprises; MNE= multi-national enterprises

Personnel mobility

The mobility of human resources carries a wide range of marked and impressive effects depending on or according to the systems in which or between which it happens – national systems, regional systems, sectoral systems, technological systems, and social systems (Pogue, 2007). Nevertheless, according to Stevens (1997) "the movement of people and the knowledge they carry with them are vital to the dissemination of innovation – often, not through some specific form of knowledge, but rather the general approach to innovation and competence in solving problems". As stressed by OECD (2016), the movement of highly educated people worldwide at different levels of their own individual professions is considered an important and necessary driver of the circulation and/or dissemination of knowledge globally. In fact, it is also well known that many institutions or even countries are engaged in global competitions to scout for relevant skills and/or talents so as to establish their own global scientific and technological centres of excellence (OECD, 2016).

A very good historical example of human mobility was the influx of highly skilful British miners in the late nineteenth and early twentieth centuries to work in the gold mines of the Witwatersrand in South Africa (Pogue, 2007). Another good example, is the diffusion of early industrial technologies into Europe in the early eighteenth century due to the movement of British immigrant workers (Mathias, 2013; Pogue, 2007).

Table 4.11 shows a few selected examples of countries with which South African government has signed bilateral agreements and/or memorandum of understanding (MoU) in various aspects of South African economy.

Table 4.11. Selected examples of South African bilateral agreements / memorandum of understanding with other countries

S/No.	**Country**		**Nature of agreement**	**Reference**
1	Republic of China		The countries have in an agreement of working together in various areas including ecosystems pertaining to wetland and desert, and the conservation of wildlife. The agreement also include collaborations in appropriate policies and regulations, monitoring and enforcement of compliance, research and development, capability building for institutions and training of manpower	(SA/China, 2000)
2	Mozambique		This MoU promotes and encourages the two countries to work together in sectors such as management, conservation, biodiversity protection, enforcement of the law, complying with responsibilities coming	(SA/Mozambique, 2014)

			from cities, other forms of conventions and legislation that are grounded on principles of reciprocal benefits and equality	
3	Japan		This programme aims at playing a significant part in advancing science between the two nations by financing collective activities in specific research areas; the agreement also gives a chance to emerging researchers to have meetings and interact; encourage the growth of fundamental research and thus play meaningfully to research capability building and development	(SA/Japan, 2003)
4	BRICS		The purpose of this MoU is to set up an institutional partnership between the parties through a framework for multilateral cooperation. The activities contemplated under the MoU aim at promoting and strengthening the cooperation between the two nations on issues of competition pertaining to law and policy via sharing of information and best practices, as well as through capacity building activities	(SA/BRICS, 2016)
5	BRICS		The objective of the MoU is to form a cohort of professionals with relevant qualifications, inspired, necessary critical thinking expertise, capacity to creating and implementing innovative resolutions with respect to problems of economic and social nature. In addition, there is need to have professionals with requisite skills to communicate and interact in multicultural and/or	(BRICS, 2015)

			ethnic environment and who have the ability to combine various types of knowledge such as traditional and science including present-day technologies	
6	UK		The objective of this MoU is to intensify clinical/technical expertise and to take a look at the best practice in the delivery of health care	(SA/UK, 2003)

4.2.2 Innovation capability building strategies for nanotechnology in South Africa

It is clear from the review of literature from various scholars that the effects of science, technology and innovation are crucial to any country's economic development and competitiveness (Atta-Mensah, 2015; Krammer, 2017; UNCTAD, 2019). Basically, increased levels of activities in the three focus areas (i.e., science, technology and innovation) are necessary and may subsequently assist any country to attain its technological and economic ambitions (DST, 2015).

At the moment South Africa has endeavoured to build capabilities and has made headways in the development and application of nanotechnology in many areas. Some of the capability building strategies that the government has created for nanotechnology are discussed herein.

National Nanotechnology Strategy

In particular, and relevant to the current research study in this report, South Africa developed the national nanotechnology strategy in 2005 (see also **Subsection 4.2.1**) with the objective of ensuring that South Africa prepares herself to use nanotechnology so that it increases her international competitiveness coupled with sustainable economic growth (DST, 2005). Some of the elements of the plan for the nanotechnology strategy include “develop human resources and supporting infrastructure, support the creation of new devices; and support long-term nanoscience research” (Harsh et al., 2017).

More specifically, six areas in which nanotechnology can create real benefits for South Africa were singled out in the national nanotechnology strategy, namely, “water, energy, health, chemical and bioprocessing, mining and minerals, and advanced materials and manufacturing” (DST, 2005). The six areas were further divided into two developmental clusters. Firstly, the industrial development clusters. This cluster comprises of mining and minerals, chemical and bioprocessing and materials and manufacturing. There is no doubt that, over the years, promoting industrial development (or industrialisation) is the key solution to developing countries’ economies (Pakes, 1998). As for South Africa, the industrial cluster, has the advantage of benefiting from the strength that the country has in nanotechnology (DST, 2005).

The second cluster (social development clusters) include water, energy and health. The Importance of this cluster is that new and advanced developments in the supply of purified or clean water, inexpensive and renewable (or non-depleted) energy and better primary (or initial) health care would benefit the majority of poor people in South Africa (DST, 2005). A study by Harsh et al. (2017) also emphasizes that the social development cluster aims to create pro-poor technologies.

Locating the nanotechnology strategy in the South African strategy landscape

According to DST (2005) and Dube and Ebrahim (2017), the national nanotechnology strategy is deeply embedded within the developmental objectives of South Africa such that it is able to compliment other national strategies such as “advanced manufacturing technology strategy, biotechnology strategy, and the skills development strategy”. In other words, the nanotechnology strategy directly and/or indirectly plays a part in the innovation undertakings and objectives of other strategies.

Public funding

According to Bhattacharya, Sujit et al. (2012) funding nanotechnology is one of the high priority areas in both advanced and emerging economies due to the technology’s promise to provide solutions in high technologies and also the possibility of new pathways for alleviating crucial technological and economic developmental issues. South Africa is not an exception to the global trend. For example, at the start of the innovation strategy, the South African government pledged an investment of R170 million in nanotechnology over the first three years of a 10 year plan (DST, 2006; Musee et al., 2010). As outlined by DST (2005), some of the items that were earmarked for funding include, (1) capacity building (i.e., R&D, and human resource development), (2) research and innovation networks, (3) flagship projects (i.e., six areas discussed already under national nanotechnology strategy), (4) R&D infrastructure, and (5) characterisation centres.

National nanotechnology equipment programme

The South African government recognises that infrastructure of world-class research and innovation involves major pieces of equipment that require substantial financial investment for its purchase and costs during its operations (NRF, 2015). It is for this reason that the DST has, over the years, devoted some money in its yearly budget for acquisition of key research equipment (NRF, 2015). Two such infrastructure project funding initiatives, national equipment programme (NEP) and national nanotechnology equipment programme (NNEP) are aimed at supporting the purchase, improvement or development of the latest equipment for South African researchers. In particular, the NNEP formed part of the implementation of the national nanotechnology strategy that was aimed at supporting the acquisition of research equipment for the analysis and characterisation of nanomaterials (NRF, 2015). Unfortunately, the NNEP ended in 2015, after a 10-year investment programme that cost over R400 million (Dube & Ebrahim, 2017).

Nanotechnology innovation centres

To move nanotechnology research forward, innovation centres for nanotechnology have been established at Mintek and at the CSIR (DST, 2008). “These multi-user national facilities play a significant role in promoting nanotechnology research, with their primary focus leaning more towards the higher end of the innovation value chain, namely the development of commercial products and processes” (DST, 2008). The two centres of nanotechnology innovation possess some of the latest and highly advanced equipment needed to do research that is far ahead or advanced in the field. Such research is mainly conducted in accordance with the objectives of the national nanotechnology strategy. As the centres of nanotechnology innovation are facilities of the nation, they are available to all researchers working in the field of nanotechnology (DST, 2008).

Human capital development

The OECD (2001) defines human capital as “the knowledge, skills, competencies and attributes embodied in individuals that facilitate the creation of personal, social and economic well-being”. In addition, Marimuthu et al. (2009) refer to human capital as “processes that relate to training, education and other professional initiatives in order to increase the levels of knowledge, skills, abilities, values, and social assets of an employee which will lead to the employee’s satisfaction and performance, and eventually on a firm performance”. Incidentally, for nanotechnology, Bhattacharya, Sujit et al. (2012) state that nanotechnology requires various skills in order to understand and/or master the technology since knowledge in the area is changing constantly and very rapidly such that there is very high uncertainty at all times. Therefore, Musee et al. (2010) states that “human capital development by South Africa is an important aspect because of the need to produce a generation of scientists and researchers that are suitably qualified to ensure safe and responsible development of a nanotechnology-based industry in South Africa”. Ideally, the field of nanotechnology is highly based on scientific principles, and thus, its success depends on strong scientific capabilities.

Two mechanisms have been suggested for developing skilled nanotechnology workforce, namely, (1) curriculum-based training approach, and (2) introduction of research chairs (Musee et al., 2010). **Table 4.12** shows South African universities that are involved in the teaching and/or training of students in nanotechnology related fields where as **Table 4.13** shows research chairs pertaining to nanotechnology at South African Universities.

Table 4.12. South African universities offering MSc in nanoscience qualification through collaboration (Dube & Ebrahim, 2017)

S/No.	University
1	University of the Western Cape (the program-managing institution)
2	University of Johannesburg
3	University of the Free State
4	Nelson Mandela Metropolitan University

According to Dube and Ebrahim (2017) “students undergo 9 months of didactic learning, followed by a research project that can be completed at any one of the participating universities, under the stream of either nanochemistry, nanophysics, or nanomedicine”.

Table 4.13. Nanotechnology related research chairs initiative (NRF, 2018a)

S/No.	Name of research chair	University holder
1	Medicinal chemistry and nanotechnology	Rhodes University
2	Functional nanostructural materials	Stellenbosch University
3	Nano-materials for catalysis	University of Cape Town
4	Nanotechnology	University of Johannesburg
5	Nano-electrochemistry and sensor technology	University of the Western Cape
6	Nanotechnology	University of Johannesburg
7	Nanophotonic	Nelson Mandela University

Furthermore, South Africa has also launched a number of international collaborations with other countries as a form of capability building strategy for nanotechnology in areas of research, human development and innovation (DST, 2008).

DST-NRF centre of excellence in strong materials

The DST-NRF centre of excellence in strong materials (CoE-SM) was established and funded by DST and NRF in June 2004 as a research network of seven South African universities and two science councils (Cornish, 2019). It is housed at Wits University and enables researchers to collaborate across and/or within disciplines and institutions, both locally and abroad (Cornish, 2019). The research network created by CoE-SM over the years has enabled both researchers and students to access the required skills and equipment located at the institutions participating within the centre (Cornish, 2019).

According to Cornish (2019), the CoE-SM’s research focus is mainly in six areas, namely, “carbides and cermets; carbon nanotubes and strong composites (i.e., nanotechnology based materials); ceramic materials; diamond, thin hard films and related materials; and new ultra-hard materials and strong metallic alloys”.

The following table (**Table 4.14**) shows some of the highlights and/or achievements of the centre since June 2004 (Cornish, 2019).

Table 4.14. Consolidated achievements of DST-NRF centre of excellence in strong materials since 2004 (Cornish, 2019)

S/No.	Achievements
1	A host of more than 50 researchers from various universities or parastatal research institutions
2	Supporting more than 60 postgraduates from various disciplines every year
3	Supporting a small number of honours students, or 4th year engineering students in their research projects
4	Graduated over 180 postgraduates by the end of 2018
5	Published more than 660 research papers
6	Produced 8 patents, and more patents are still pending
7	The researchers in the centre have won various awards including, (1) the NST/BHP Billiton awards (2012-2013), (2) the Louw Alberts wards (2015), and (3) the Merck medal (2015)

4.3 Technological catch-up in water treatment and medical related nanotechnology-based processes and/or products

The main purpose of this section is to report the results of the performance of South Africa compared to other BRICS nations during the period 2010-2018 in terms of scientific publications and patents. The USA also formed part of the study because it is considered a prolific research nation. **Subsections 4.3.1** and **4.3.2** outlines the results of water treatment and medical related nanotechnology-based processes and/or products, respectively. As discussed in **Chapter 3** the data on scientific productivity (publications) was obtained from the SCI via the Web of Science platform whereas the study used patent data (technological performance) from WIPO which incorporates various databases.

4.3.1 Technological catch-up in water treatment

In a recent report by WRC (2018) it states that “water is a strategic resource critical for basic human needs and for powering key economic sectors such as agriculture, food processing, manufacturing and resource extraction”. Unfortunately, South Africa is considered as a water-scarce country (Muller et al., 2009). As a result, a number of researchers are carrying out research related to water and wastewater treatment in South Africa with a view of coming up with innovative solutions that would alleviate the problem of water-scarcity. In the recent past, the advent of nanotechnology has shifted the focus in water and wastewater treatment research from using conventional materials to nanotechnology-based materials (Simate et al., 2012). This study assesses the extent to which nanotechnology has advanced technological catch-up in water treatment in South Africa. The results presented in this section compares South Africa and other BRICS nations during the period 2010-2018 in terms of scientific publications and patents. The USA is also included because of its world-class status in research and innovations.

Publications in water treatment

This subsection presents results of nanotechnology-based water treatment techniques in form of the number of publications. Publication results are widely accepted as a measure of performance and/or productivity of researchers (Carpenter et al., 2014; Sargent Jr, 2016). **Figure 4.1** indicates the number of articles produced by each of the countries in the study in the period 2010-2018. The USA is leading in the number of research articles produced followed by China and India. On the other hand, **Figure 4.2** shows a similar trend on a year-by-year basis. However, there have been fluctuations in the number of publications between China and India in terms of leadership on a year-by-year basis.

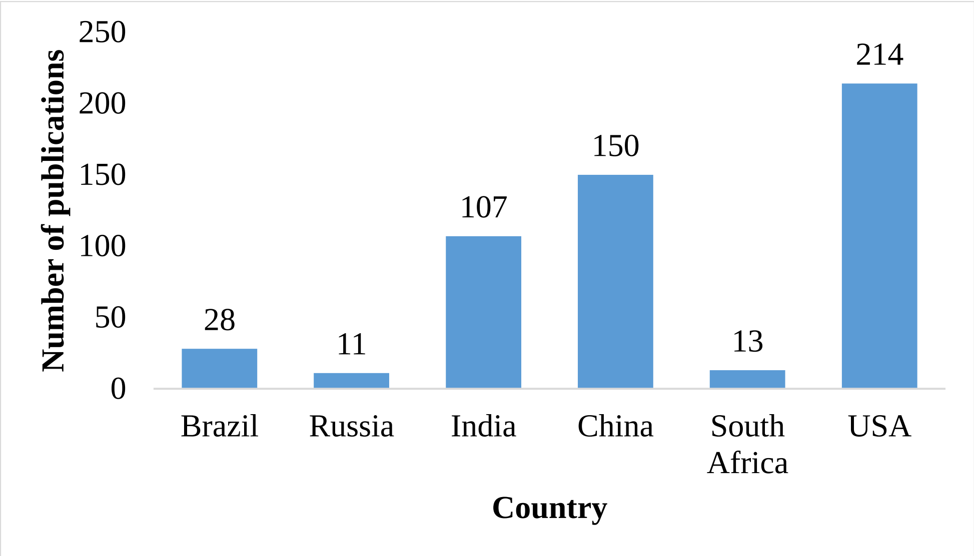

Figure 4.1. Number of research articles related to nanotechnology based water treatment from 2010-2018

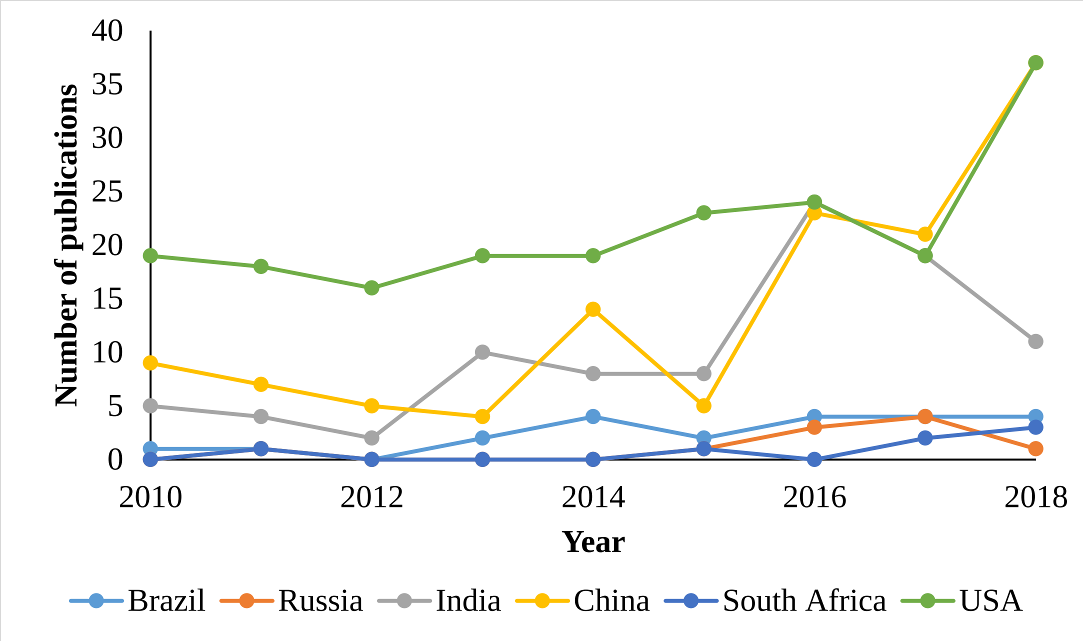

Figure 4.2. Number of research articles related to nanotechnology based water treatment on a year-by-year basis from 2010-2018

Citations of the publications in water treatment

Citation of one's research work by peers is one of the recognised indicators for assessing research impact or its quality (Aksnes et al., 2019). Therefore, this section reports the impact of research of various countries in the study based on citations. **Figure 4.3** gives citations of research articles related to nanotechnology based water treatment on a year-by-year basis from 2010-2018. The figure shows that the USA is leading in the number of citations of research articles followed by India and China. Russia and South Africa are at the bottom of the trend.

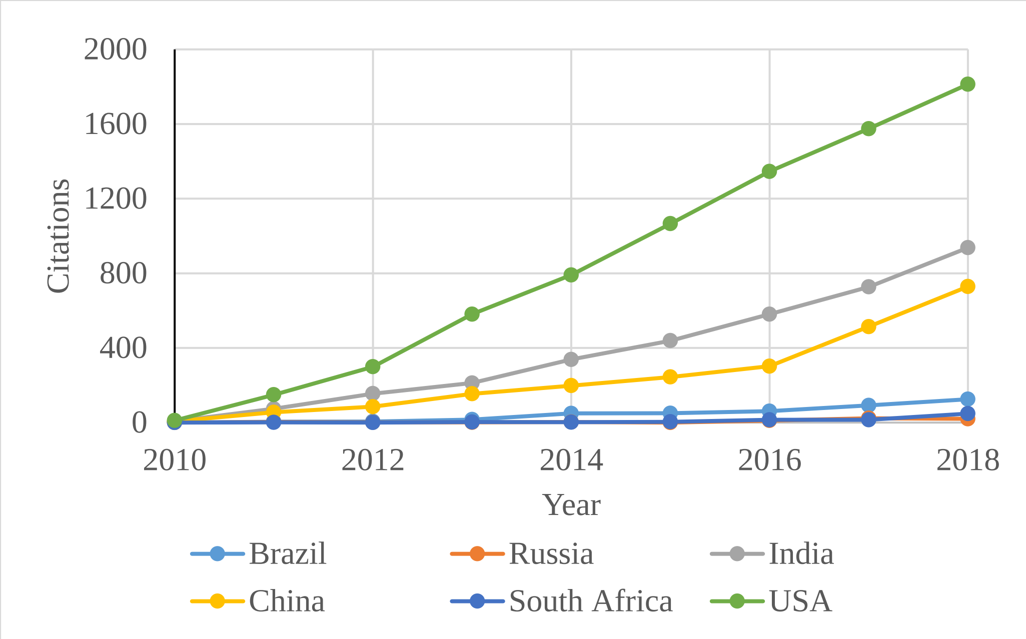

Figure 4.3. Citations of research articles related to nanotechnology based water and wastewater treatment on a year-by-year basis from 2010-2018

Collaborations amongst countries in the publications in water treatment

International scientific collaboration which involves the sharing of research data, equipment sharing, joint experimentation, building of databases and conferences has grown in recent years (Srivastava, 2012). **Table 4.15** shows the number of research articles produced during scientific collaborations amongst the countries under the study. When **Table 4.15** is compared with **Figure 4.1,** it is clear that countries that have high number of articles through scientific collaborations also have high publication rate. For example, the USA, China and India follow the same order of publication rate (**Figure 4.1**) as that of the number of articles generated through scientific collaborations (**Table 4.15**).

Table 4.15. Scientific collaborations amongst countries in nanotechnology-based water treatment research articles

	Countries studied and number of articles through scientific collaborations					
Collaborating Countries	Brazil	Russia	India	China	South Africa	USA
Saudi Arabia	0	1	7	0	3	5
India	0	2	-	0	2	8
China	0	0	0	-	2	26
USA	2	0	8	26	2	-
Belgium	0	0	1	0	1	0
Nigeria	0	0	0	0	1	0
South Korea	2	0	7	5	1	14
South Africa	0	0	0	2	0	0
England	2	0	0	4	0	8
Switzerland	0	0	0	0	0	5
Denmark	1	0	0	2	0	0
Malaysia	0	0	6	0	0	0
Iran	0	0	4	2	0	2
Israel	0	0	0	0	0	3
Italy	0	0	3	0	0	8
Germany	0	0	0	0	0	7
Canada	0	0	2	5	0	6
France	0	0	2	0	0	6
Pakistan	0	0	2	0	0	0
Qatar	0	0	2	0	0	0
Russia	0	0	2	0	0	0
Argentina	0	0	1	0	0	0
Australia	0	0	1	5	0	0
Scotland	0	0	0	2	0	2
Japan	0	0	0	2	0	0
Austria	0	0	0	1	0	0
Singapore	0	0	0	3	0	0
Egypt	0	0	0	3	0	2
Thailand	0	0	0	3	0	0
Mexico	0	0	0	0	0	2
Total number of research articles by the country under study	28	11	107	150	13	214
Total number of research article through collaborations	7	3	48	65	12	102
Collaborations as a percent of the number of research article by the country under study	25.0	42.9	44.9	43.3	92.3	47.7

Disciplines and/or research areas in the publications in water treatment

Applications of nanotechnology spans several domains such as chemistry, electronics, high-density magnetic recording media, sensors, biotechnology, water treatment, etc., (Capek, 2006). **Figure 4.4** shows the areas related to water treatment in which nanotechnology research is carried-out and/or applied. The figure clearly shows that application of nanotechnology in water and wastewater treatment is broad-based and multidisciplinary. The various areas given in Figure 4.4 which incorporate nanotechnology-based materials can be used and/or explored by engineers and scientists in the treatment of water and wastewater. For example, for energy fuels research area, microbial fuel cells (MFC) that have a demonstrated ability to produce bioenergy and treat wastewater simultaneously are using nanomaterials for their anodes (Salar-García & Ortiz-Martínez, 2019). Research has shown that the nanomaterials enhance the electron transfer mechanisms between microorganisms, which act as biocatalysts in the anode chamber, and the material forming the anode electrode itself thus increasing current generation (Salar-García & Ortiz-Martínez, 2019)

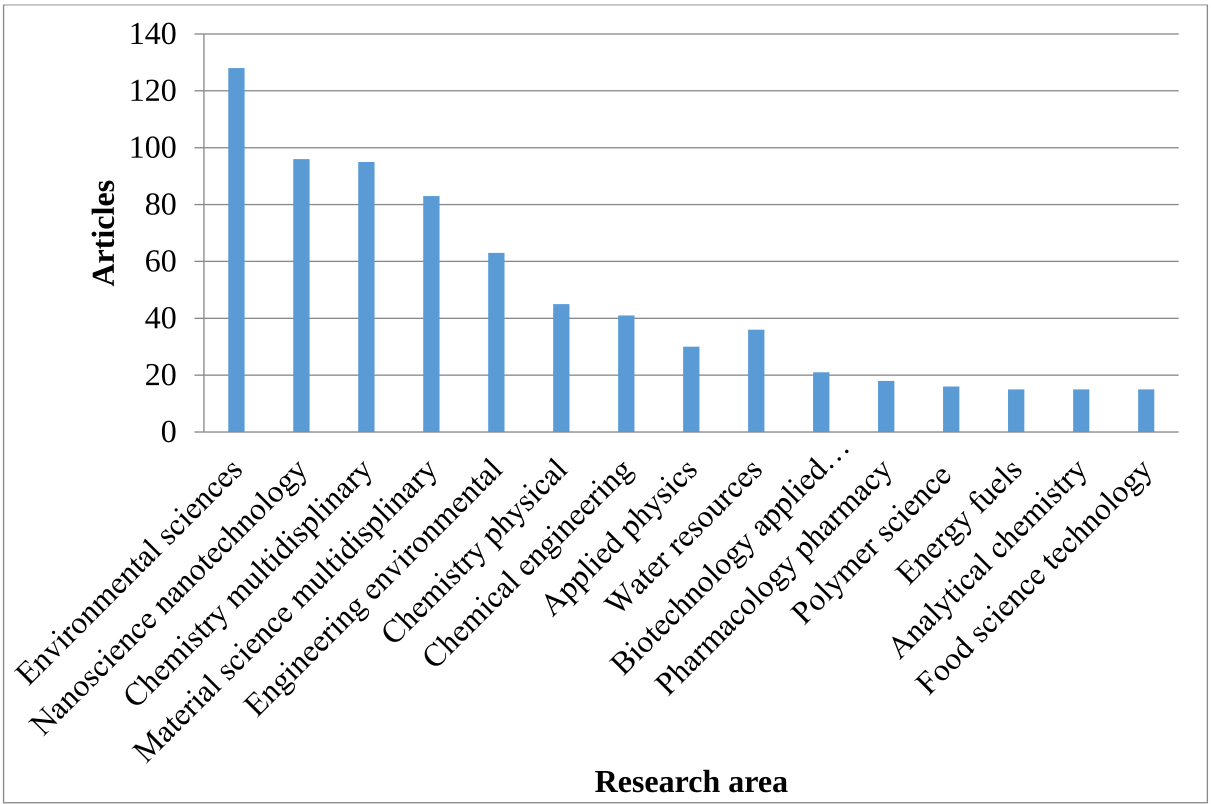

Figure 4.4. The areas related to water treatment in which nanotechnology research is carried-out and/or applied from 2010-2018

Patents in water treatment

It is noted that "within firms (or even at state level), detailed information about technological advances is needed so that a firm (or state) can take the right decisions concerning the amount of resources to devote to innovation, to select the fields where innovation promises economic returns and to manage innovative strategies within firms (or state)"(Archibugi & Planta, 1996). Patents, as discussed in **Section 2.8** of **Chapter 2,** are one of the ways used by researchers to collect data and information on the technological performance and/or innovative activities of firms (or the state) (Archibugi & Planta, 1996). **Figure 4.5** shows patents filled through WIPO by countries in the study with respect to nanotechnology based water treatment processes and/or products over a nine year period where as **Table 4.16** indicates the patents filled on a year-by-year period.

Figure 4.5 shows that the USA is leading in the number of patents filed over a nine year period. A combination of patents filed by the rest of the other nations is only about 8.9% of what the USA has filed in the past nine years. It is also noted from **Table 4.16** that the USA is still leading in the number of patents filed on a year-by-year basis followed by China, Russia and India, respectively. South Africa has not filed any patents during the nine year period and Brazil has filed less than five patents. Nevertheless, **Table 4.16** also shows that South Africa had filed about 20 patents before 2010.

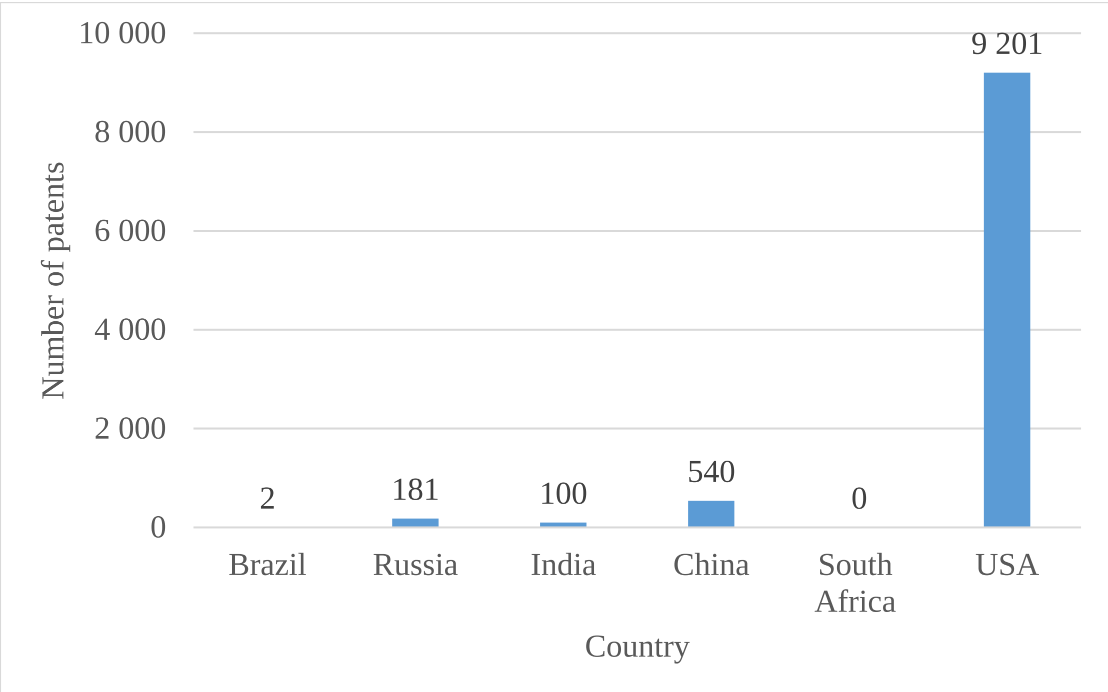

Figure 4.5. Number of patents filed through world intellectual property organisation related to nanotechnology based water treatment processes and/or products over a nine year period

Table 4.16. Number of patents filed through world intellectual property organisation related to nanotechnology-based water treatment processes and/or products on a year-by-year period

Year	Brazil	Russia	India	China	South Africa	USA
2010	0	17	60	103	0	861
2011	1	12	38	89	0	850
2012	0	12	0	38	0	879
2013	0	18	0	14	0	902
2014	1	22	1	80	0	1033
2015	0	28	0	33	0	1099
2016	0	21	0	18	0	1012
2017	0	32	0	63	0	987
2018	0	12	0	65	0	901
Patents before 2010	4	287	288	864	20	11969

Top 10 applicants for patents in water treatment

Table 4.17 shows the number of nanotechnology-enabled water treatment patent applicants granted to BRICS countries including the USA by WIPO from 2010-2018. The table shows the top 10 applicants in terms of the number of patents granted during the period.

From the table it is seen that patent applications are mainly from firms and universities though a few individuals are also involved in patent applications, particularly, in South Africa. It is also seen that apart from the USA, other countries such as Russia, India and China have patents applied through some universities in the USA. This may be attributed to the fact that the USA has some of the best universities in the world dealing in nanotechnology research (StatNano, 2018).

Table 4.17. Top 10 applicants for patents in water treatment

	Applicants for patents	No. of patents
Brazil	Auspex Pharmaceuticals, Inc; Schering Corporation; Universidade Federal de Minas Gerais	1 1 1
Russia	Massachusetts Institute Of Technology; The Broad Institute Inc.; President And Fellows Of Harvard College; The Brigham And Women's Hospital, Inc.; Wake Forest University Health Sciences; Yoo, James;	15 10 9 5 5 5

	Atala, Anthony; Soker, Shay; The Regents Of The University Of California; Alexis, Frank;	4 4 4 3
India	Astrazeneca AB; Ferrari, Mauro; The Regents Of The University Of California; Board Of Regents Of The University Of Texas System; Massachusetts Institute Of Technology; The Brigham And Women's Hospital, Inc.; Alexis, Frank; Basto, Pamela; Erez, Adi; Erez, Oded	7 7 7 6 5 5 4 4 4 4
China	Shanghai National Engineering Research Center For Nanotechnology Co., Ltd.; Massachusetts Institute Of Technology; The Regents Of The University Of California; Astrazeneca AB; Ferrari, Mauro; Northwestern University; Board Of Regents Of The University Of Texas System; Board Of Regents, The University Of Texas System; E. I. Du Pont De Nemours And Company; Golakoti, Trimurtulu	91 17 13 8 8 8 7 7 7 7
South Africa	Electrokinetic Limited; Glendinning, Stephanie; Jones, Colin, John, Francis, Philip; Covalent Partners LLC; Lamont-Black, John; Smithkline Beecham Corporation; Baba, Atsuo; Baldoni, John, M.; Cooper, David, Neil; Denison, Ginger, M.;	3 3 3 2 2 2 1 1 1 1
USA	The Regents of the University of California; Massachusetts Institute of Technology; The Regents Of The University Of California; Fuji Film Corporation; North Western University; President and Fellows of Harvard College; International Business Machines Corporation;; Board of Regents, The University of Texas System National Tsing Hua University; GP Medical, Inc.;	185 179 117 102 88 72 65 61 58 52

4.3.2 Technological catch-up in medical fields

According to the South African Human Rights Commission, SAHRC (2002), "the right to health is fundamental to the physical and mental well-being of all individuals and is a necessary condition for the exercise of other human rights including the pursuit of an adequate standard of living". In fact, according to Maresova et al. (2015), "the high quality of public health improves not only healthy life expectancy, but also the increased quality and productivity of labour". Unfortunately, the South African government has had a number of challenges related to the health of South Africans since 1994 (Harrison, 2009). Nevertheless, over several years, enormous efforts have been made to improve various features of health and healthcare not only in South Africa, but globally as well (WEF, 2019). Most importantly, the investments in the medical device industry and pharmaceutical products as part of health care have become more significant (IFPMA, 2017; Maresova et al., 2015).

This particular study focuses on the performance of medical products and/or processes incorporated with nanotechnological materials in the advancement of technological catch-up by South Africa. Several studies including Simate and Yah (2014) have indicated that nanotechnological materials such as carbon nanotubes have found widespread applications for drug delivery amongst a wide range of other uses in biomedical and biotechnology. As in the previous section, the results presented in this section compare South Africa and other BRICS nations. The results of the USA are also included because of its leadership in research and innovations. All the research articles and patents dealing with medical related products and/or processes during the period 2010-2018 were carefully selected using keywords identified by Wong et al. (2007) as described in **Subsection 3.5.2**.

Publications in medical fields

According to Pope et al. (2001) success in the field of medical innovation is measured by scientific presentations, published papers, patents, and receipt of grants. This particular subsection reports the results of nanotechnolog based published papers in the medical fields. **Figure 4.6** shows the publications from BRICS countries and the USA over a nine year period where as **Figure 4.7** shows the publications on a year-by-year basis.

Both **Figure 4.6** and **Figure 4.7** show that the USA is leading other nations both in the number of research articles produced during 2010-2018 and in number of research papers produced on a year-by-year basis. From the two figures (**Figure 4.6** and **Figure 4.7**) the rest of the other nations are in the the following order: China > India > Barazil > Rusia > South Africa.

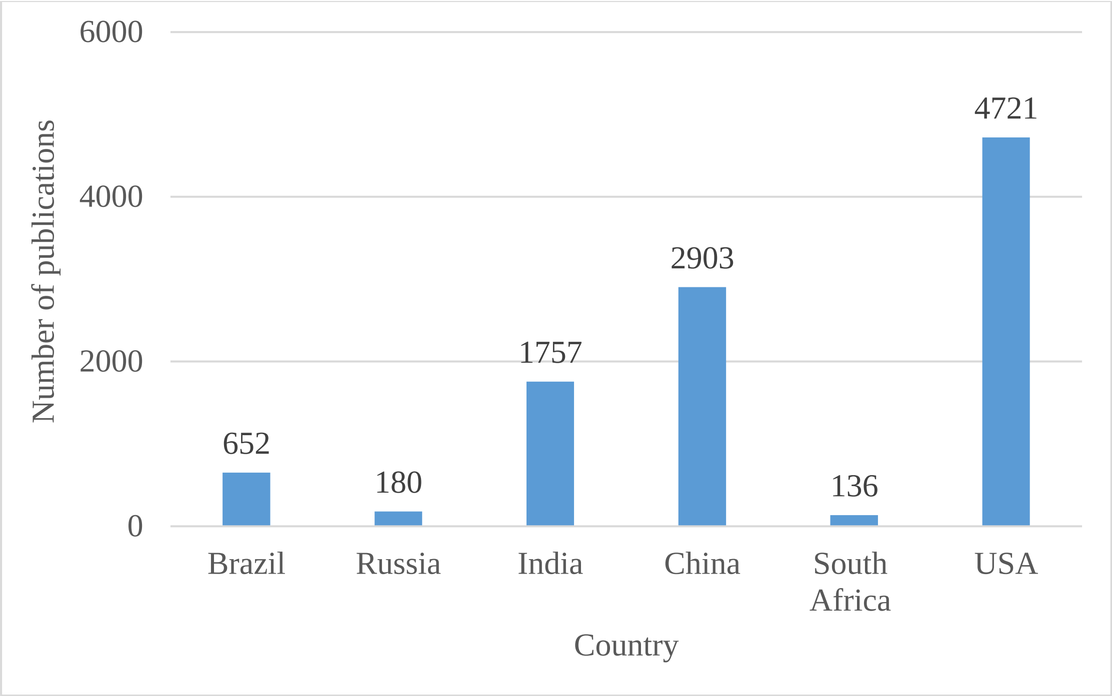

Figure 4.6. Number of research articles related to nanotechnology based medical fields from 2010-2018

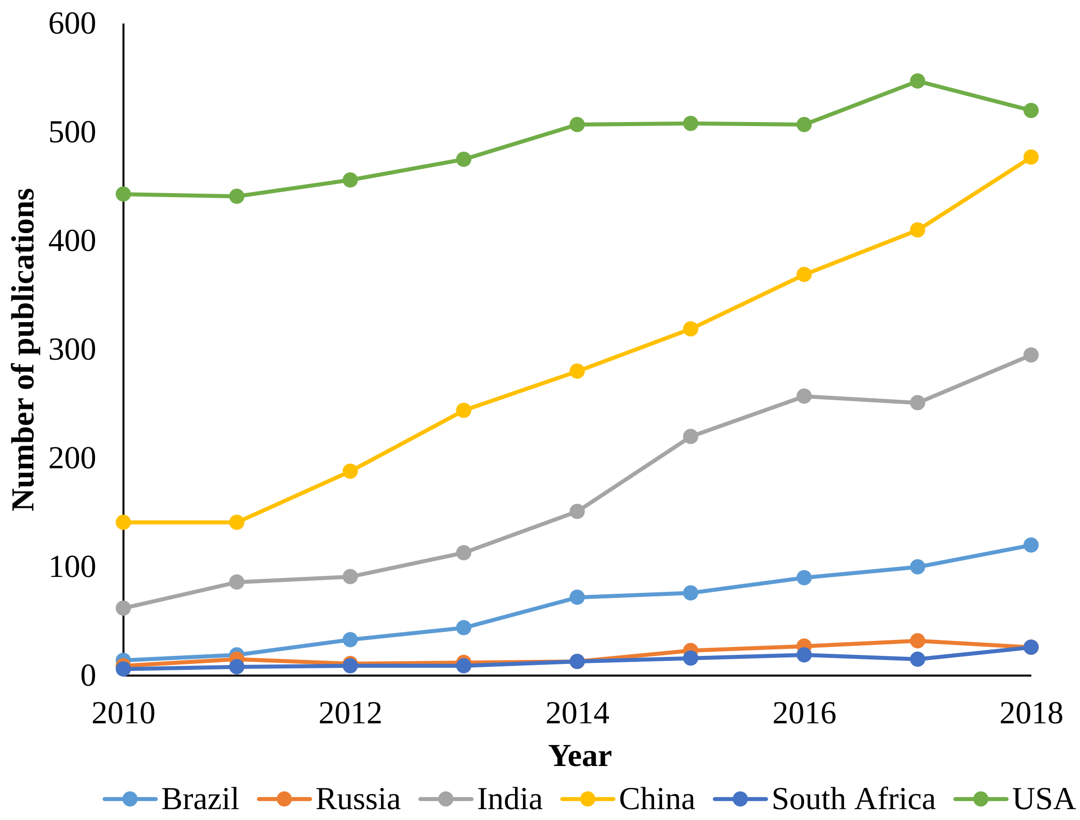

Figure 4.7. Number of research articles related to nanotechnology based medical fields on a year-by-year basis from 2010-2018

Citations of the publications in medical fields

Li et al. (2015) state that "the impact of a publication in a particular medical area is reflected by the number of times the article is included as a citation". **Figure 4.8** shows the citations of the publications over a nine year period generated in the field of medicine. In particular, the figure looks at citations of publications that incorporated nanotechnological materials during the research studies in the articles.

The trend in the number of citations of the publications over a nine year period (**Figure 4.8**) is similar to the trend in the number of published research articles (**Figure 4.6**), i.e., USA > China > India > Brazil > Russia > South Africa. According to Bornmann et al. (2008) "the publication of a research paper serves to disseminate the results of the research and at the same time 'invites' other scientists to use the findings in their own research". Therefore, it is expected that the order for the number of citations of the publications is similar to the trend in the number of published research articles as confirmed in the figure below.

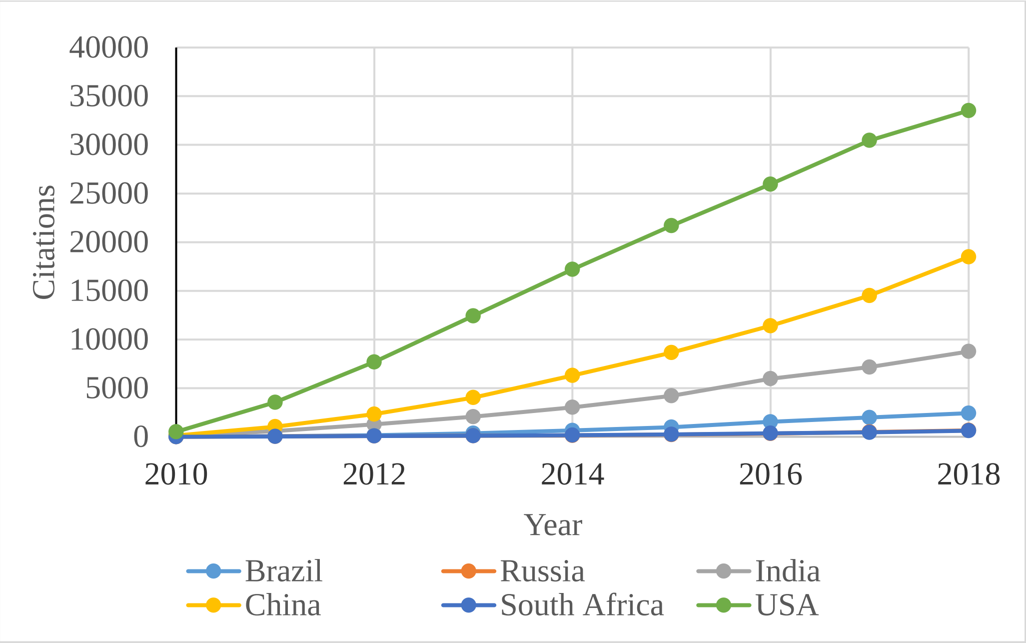

Figure 4.8. Citations of research articles related to nanotechnology based medical fields on a year-by-year basis from 2010-2018

Collaborations amongst countries in the publications in medical fields

It is widely acknowledged that scientists and many other professionals have greater impact when they collaborate locally and/or internationally (Varnai et al., 2017). This subsection reports results (**Table 4.18**) of the countries that collaborated with the BRICS countries and the USA in various fields of medicine that incorporated nanotechnological materials in their research from 2010-2018.

Similar to water treatment, **Table 4.18** when compared with **Figure 4.6** clearly shows that countries that have a high number of articles through scientific collaborations also have high publication rate. For example, all countries follow the same order of publication rate as that of the number of articles generated through scientific collaborations, i.e., USA > China > India > Brazil > Russia > South Africa.

Table 4.18. Scientific collaborations amongst countries in nanotechnology-based medical fields research articles

	Countries studied and number of articles in scientific collaborations					
Collaborating Countries	Brazil	Russia	India	China	South Africa	USA
Saudi Arabia	0	5	89	32	4	81
India	30	7	0	29	13	130
China	8	6	29	-	0	553
USA	50	25	130	553	14	0
Taiwan	0	0	18	0	0	0
Pakistan	0	0	0	40	0	0
South Korea	0	0	66	36	0	127
Greece	0	0	0	0	5	
England	8	0	20	68	6	172
Brazil	-	0	30	0	0	
Romania	0	5	0	0	0	0
Malaysia	0	0	43	0	4	
Iran	0	0	0	0	0	62
Israel	0	5	0	0	0	
Italy	15	6	46	21	0	118
Germany	16	9	0	0	3	155
Canada	9	0	21	59	3	111
France	17	9	19	27	3	70
Pakistan	0	0	0	0	3	0
Finland	0	7	0	0	3	0
Ecuador	0	0	0	0	2	0
Argentina	8	0	0	0	0	0
Australia	8	7	39	64	0	67
Poland	6	0	0	0	0	0
Japan	0	0	25	41	0	59
Chile	5	0	0	0	0	
Singapore	0	0	23	88	0	56
Egypt	0	0	0	0	2	0
Portugal	20	5	0	0	0	0
Spain	24	5	0	0	3	63

Turkey	0	4	0	0	0	0
Netherlands	0	0	0	18	0	0
Total number of research articles by the country under study	652	180	1757	2903	136	4721
Total number of research articles through collaborations	224	105	598	1134	68	1824
Collaborations as a percent of the number of research articles by the country under study	34.4	58.3	34.0	39.1	50.0	38.6

Disciplines and/or research areas in the publications in medical fields

There are various medical fields, including respiratory medicine, oncology, emergency medicine, critical care medicine, rehabilitation, otolaryngology, obstetrics and gynecology, ophthalmology, anesthesiology, dermatology and many more (Li et al., 2015; MBA, 2018). This particular subsection reports results (see **Figure 4.9**) of a number of areas within some of the medical fields that incorporated nanomaterials in their published articles already reported in the previous subsections.

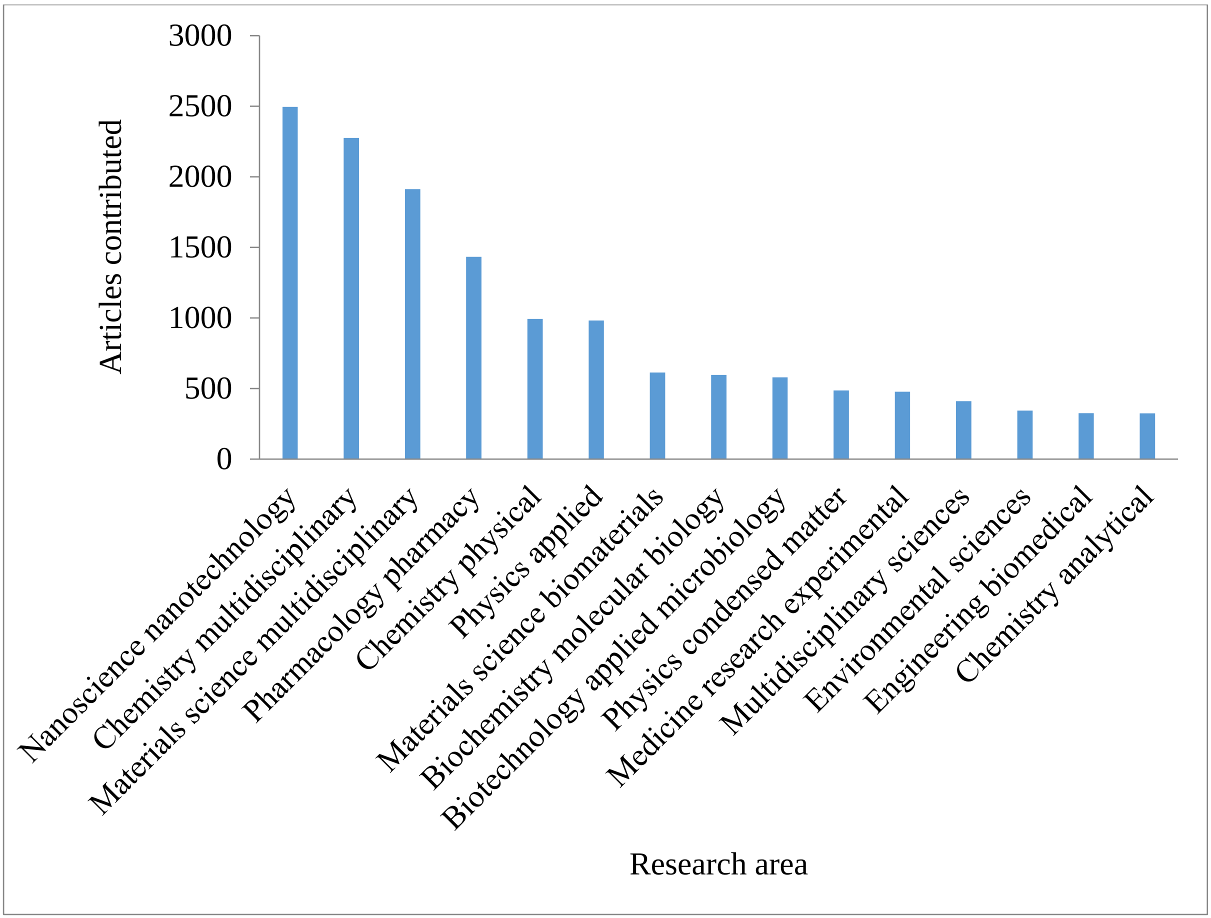

Figure 4.9. The areas related to medical fields in which nanotechnology research is carried-out and/or applied from 2010-2018

The number of fields shown in **Figure 4.9** is an indication that, firstly, nanotechnology encompasses a wide and diverse range of materials, tools and approaches (Roco et al., 2011; RoyalSociety, 2004); secondly, the application of nanotechnology to the medical field is broad-based and multidisciplinary. Moreover, the medical field itself is composed of various disciplines (Li et al., 2015; MBA, 2018).

Patents in medical fields

The significance of patents as a measure of the country's technological performance has been reiterated by several scholars (Huang et al., 2011; OECD, 2004; Pope et al., 2001). For example, Huang et al. (2011) considers them as a symbol of a country's technological advancement. Nevertheless, not all inventions are patented due to industrial secrecy and some inventions are not technically patentable notably software (Archibugi, 1992; Arundel, 2001; Fontana et al., 2013). In addition, the propensity to patent also varies across areas (Archibugi, 1992). **Figure 4.10** shows the number of patents that were filed by the BRICS countries and the USA through WIPO from 2010-2008 whereas **Table 4.19** shows the patents that were also filed through WIPO on a year-by-year period.

Both over a nine year period (**Figure 4.10**) and on a year-by-year basis (**Table 4.19**) the USA has been leading the rest of the other nations in terms of nanotechnology-based medical processes and/or products. Just like the case for water treatment processes and/or products based on nanotechnology, the other countries contribute very little to the patents filed through WIPO (4.7% of what the USA has filed in the past nine years). South Africa has not filed any patents during the nine year period and Brazil has filed only about 20 patents. As stated earlier, some countries like South Africa may not be patenting their inventions due to industrial secrecy. Therefore, patenting on its own may not be a good indicator of technological adavancement.

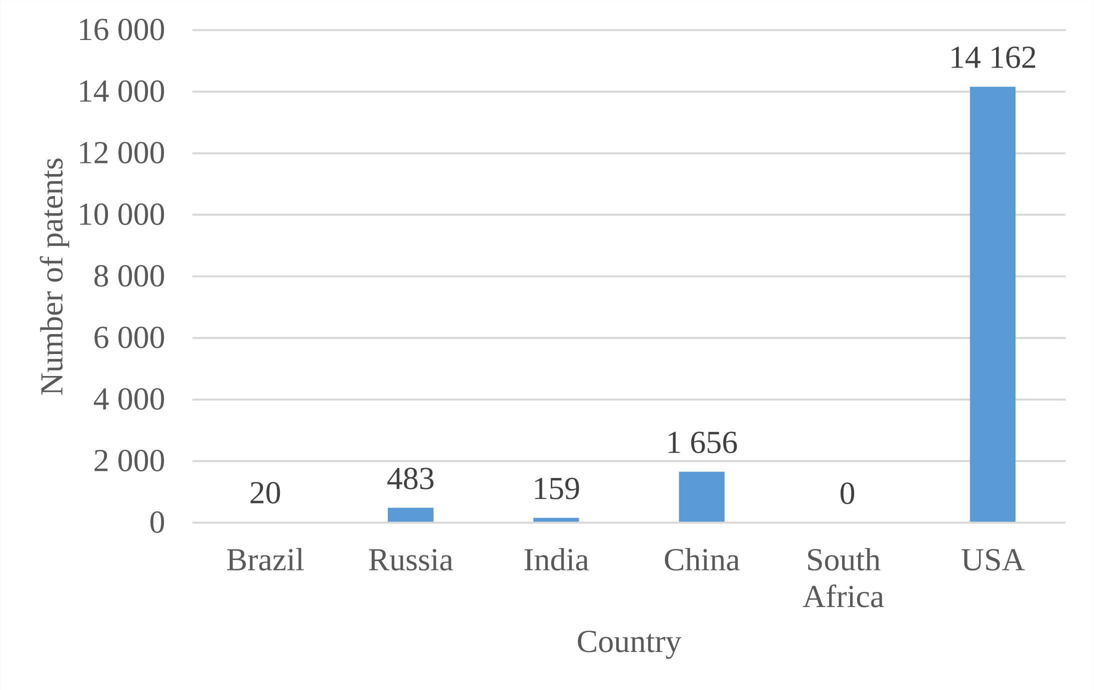

Figure 4.10. Number of patents filed through world intellectual property organisation related to nanotechnology based medical field processes and/or products over a nine year period

Table 4.19. Number of patents filed through world intellectual property organisation related to nanotechnology-based medical field processes and/or products on a year-by-year period

Year	Brazil	Russia	India	China	South Africa	USA
2010	4	27	76	189	0	1404
2011	5	23	55	221	0	1349
2012	0	25	6	131	0	1378
2013	3	40	4	109	0	1457
2014	7	41	6	192	0	1583
2015	1	55	3	132	0	1621
2016	0	71	0	99	0	1556
2017	0	69	2	182	0	1466
2018	0	73	6	271	0	1327
Patents before 2010	26	666	439	2304	36	19198

Top 10 applicants for patents in medical fields

The medical industry is a vital sector of any society and nanomedicine in particular has gained ground over the past several years. **Table 4.20** shows the number of patent applicants pertaining to the medical field filed through WIPO by the BRICS countries and the USA; the table specifically shows only the top ten applicants for each country in the 9 year period from 2010-2018.

It is clear from **Table 4.20** that most of the patent applications are from universities, and only a few firms and individuals are involved. This trend is in contrast to water treatment products and/process based on nanotechnology where patent application were mainly from both firms and universities. It is also noted from **Table 4.20** that apart from Brazil and South Africa, the rest of the other countries have patents applied through some universities in the USA. This may explain why South Africa and Brazil have low patenting capabilities; and there is no doubt that the USA has some of the best universities in the world dealing in nanotechnology research (StatNano, 2018).

Table 4.20. Top 10 applicants for patents in medical fields

	Applicants for patents	No. of patents
Brazil	Universidade de São Paulo – USP;	4
	Universidade Federal de Minas Gerais;	3
	Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP;	2
	Auspex Pharmaceuticals, Inc;	1
	Comisso Nacional de Energia Nuclear – CNEN;	1
	Embrapa - Empresa Brasileira de Pesquisa Agropecuária;	1
	Fundação Universidade de Brasília;	1
	Immunomedics, Inc;	1
	Instituto De Pesquisas Technological DO EST S. Paulo S/A IPT;	1
	Instituto De Pesquisas Technological DO EST S. Paulo S/A IPT	1
Russia	Massachusetts Institute Of Technology;	17
	Microsoft Technology Licensing, LLC;	13
	President And Fellows Of Harvard College;	10
	The Broad Institute Inc.;	10
	The Regents Of The University Of California;	9
	Henkel AG & Co. KGAA;	5
	The Brigham And Women's Hospital, Inc.;	5
	Wake Forest University Health Sciences;	5
	Yoo, James;	5
	Atala, Anthony	4
India	Massachusetts Institute Of Technology;	10
	The Regents Of The University Of California;	8
	Astrazeneca AB;	7
	Ferrari, Mauro;	7
	Board Of Regents Of The University Of Texas System;	6
	President And Fellows Of Harvard College;	6
	The Brigham And Women's Hospital, Inc.;	6
	Merck Patent GMBH;	5
	Alexis, Frank;	4
	Basto, Pamela	4
China	Shanghai National Engineering Research Center for Nanotechnology Co. Ltd.;	165
	Shanghai National Engineering Research Center for Nanotechnology Co., Ltd.;	43
	Massachusetts Institute of Technology;	31
	The Ragent of the University of Califonia;	25
	President and Fellows of Harvard College;	19
	China National Academy of Nanotechnology & Engineering;	17

	INTEL Corp; Board of Regents, The University of Texas System; Merck Patent GMBH; North Western University	12 11 10 10
South Africa	Electrokinetic Limited; Glendinning, Stephanie; Jones, Colin, John, Francis, Philip; Chevron U.S.A. Inc.; Covalents partners LLC; Hindustan Lever Ltd; Lamont-Black, John; Pemery Corp.; Smithkline Beecham Corp; Unilever N.V	3 3 3 2 2 2 2 2 2 2
USA	The Regents of the University of California; Massachusetts Institute of Technology; The Ragent of the University of California; Microsoft Technology Licensing, LLC; CommVault Systems, Inc.; President and Fellows of Harvard College; North Western University; Microsoft Corporation; International Business Machines Corporation; Board of Regents, The University of Texas System	277 227 179 156 153 118 113 105 102 84

4.4 Economic catch-up in water treatment and medical related nanotechnology-based processes and/or products

As discussed in **Section 2.8** sales data and/or market data was used in this study as a measure of economic catch-up. Lee (2013) also argues that using sales to represent catch-up, in general, is logical because sales growth is closely related to market share. Therefore, the main purpose of this section is to report the results of the sales and/or market data of final products and/or processes that incorporated nanotechnology in South Africa and other BRICS nations. The USA is also included in the study because it serves as a role model for the rest of the world when it comes to the development and manufacture of nanotechnology products and/or processes. The USA also spends a lot of funds in R&D of nanotechnology relative to other countries (Sargent Jr, 2016).

Unfortunately, quantifying the total economic impact of innovations in nanotechnology – not just wastewater treatment and medical fields – is challenging (Ouellette, 2015a). Particularly, as stated in **Section 2.8**, relevant high-quality and quantitative data pertaining to nanotechnology is difficult to collect and thus it is not readily available (Baucher et al., 2013). Furthermore, one other hurdle is that “much of the information about nanotechnology’s market value is proprietary and is in the hands of private businesses” (Ouellette, 2015a) thus it is inaccessible.

Most importantly, the safety and health effects of nanomaterials in water and medicinal applications is not guaranteed, and thus patents may exist, but commercial products may be restricted by national and international regulations pertaining to nanomaterials. In fact, according to Perkel (2016) “nanomaterials may be safe when intact, but become toxic over time, and thus are likely to cause unknown problems in the human body when the nanomaterials degrade after they have been taken up into the human cells”. A laborious review by Yah et al. (2012) also indicates that nanomaterials have safety and health implications to human beings and thus must be handled and used cautiously at all times. As for South Africa, Mufamadi (2016) summed it up and states that “the development of nanotechnology in South Africa is hampered by many barriers such as regulation, standards, health & safety issues and public perception”.

Therefore, the next **Subsection 4.4.1** only provides the results of sales and/or market data for nanotechnology-enabled products, in general, and not necessarily water treatment and medical-related nanotechnology-based products and/or processes. Ideally, the results will serve as a proxy for the sales and/or market data in the two fields. Thereafter, the sales and/or market data results for nanotechnology-enabled products, in general, are analysed in **Section 5.5** of **Chapter 5**. As discussed in **Chapter 3** the data on sales and/or market performance was obtained from various sources including research papers and reports from organisations.

4.4.1 Economic catch-up in nanotechnology in general

This section of the study particularly assesses how South Africa has used nanotechnology to enhance economic catch-up compared to the technologically-advanced nations such as the USA. Specifically, the results presented in **Table 4.21** compares South Africa and other BRICS nations including the USA. In particular, as stated earlier (see **Section 4.4**), the study only reports sales data and/or market data of nanotechnology-enabled products and/or processes in general. The results of the sales data are analysed in **Section 5.5** of **Chapter 5**; but a summary of the main findings is briefly given here.

First and foremost the data pertaining to economic impact of nanotechnology is difficult to collect and thus it is not readily available (Baucher et al., 2013; Ouellette, 2015a); and this explains why sales and market data for Brazil and South Africa is missing. Therefore, without availability of data it is difficult to ascertain whether South Africa is catching-up with the developed world using nanotechnology-based products and/or processes. Though the cross-sectional strategy was taken to access the economic impact data at various times, **Table 4.21** shows that there is considerable amount of sales and/or market of nanotechnology-based products and/or processes from the USA, China and Russia.

Table 4.21. Sales and/or market data from nano-enabled products for the BRICS nations and the USA

Country	Sale/Market	Comment	Reference
Brazil	-	No data available.	-
Russia	$15bn	The amount of $15 bn is the sales of nanotechnology-related products as of 2013. This value is about 11% above the target that was forecasted in 2007 which implies a growth in the nanotechnology industry of approximately 2.6 times from the year 2011. Furthermore, the estimate of the amount of sales of goods and services related to nanotechnology based on data collected in business surveys from 2010 in Russia gives a revenue of $6 bn per year (Ouellette, 2015a, 2015b).	(UNESCO, 2016)
India	$100 m	The report by Desai (2013) states that "currently, the Indian nanotechnology industry is valued at $100m". Unfortunately, the article cited by Desai (2013) is no longer available and thus the data could not be verified.	(Desai, 2013)
China	$144.9 bn	This is a forecast for the 2015 market based on a 2006 report	(Accenture/ Bankinter & 2006)
South Africa	-	No data available.	-
USA	$903.5 bn	This is a forecast for 2018 market based on a 2014 Lux Research report.	(Flynn et al., 2013)

4.5 Summary

This study had three main objectives. The first objective was to determine the extent to which South Africa is creating capabilities, in general, for technological and economic catch-up with the developed world. The second objective evaluated capacity building strategies in the field of nanotechnology for technological and economic catch-up, and most importantly, the third objective determined whether nanotechnology is providing a ‘critical window’ for South Africa to catch-up with the developed world. The results of the first two objectives were obtained by analysing and evaluating various government policy documents. The third objective assessed the scientific (through research publications), technological (through patents filed through WIPO) and economic (through sales/market data) performance of South Africa compared to the USA and other BRICS nations. The economic impact was evaluated using nanotechnology in general, and not necessarily the two fields due to the difficulty in obtaining sales and/or market data (see **Section 2.8** and **4.4** for more details).

Therefore, the purpose of **Chapter 4** was to give the results pertaining to the three objectives, which are subsequently discussed in **Chapter 5**.

CHAPTER 5: ANALYSIS OF THE RESEARCH FINDINGS

5.1 Introduction

This Chapter has three objectives. The first is to give an in-depth discussion and/or analysis and evaluation of South Africa's capability building strategies for technological and economic catch-up, in general, and in nanotechnology, in particular. The second objective of this Chapter is to evaluate and compare the performance of South Africa, other BRICS nations and the USA during the period 2010-2018 in terms of scientific publications and patents. Lastly, the chapter discusses sales and/or market data of nanotechnology based water and medical related products and/or processes as a measure of economic catch-up by South Africa. However, due to the difficulty in obtaining sales and/or market data as discussed in **Sections 2.8** and **4.4**, the economic impact was evaluated using nanotechnology in general, and not necessarily with respect to the two fields.

5.2 Discussion of capability building strategies for technological and economic catch-up in South Africa

The results of this study as outlined in **Chapter 4** clearly show that the most important actor in the NIS system of South Africa is the government. Through the NIS, the government has created a number of strategies that are helping South Africa to strengthen its NIS, and subsequently technological and economic capabilities.

5.2.1 Technology and innovation policy formulation: discussion

To start with, as discussed in **Section 2.6.1**, innovation policies and principles need to be formulated and applied in a manner that accommodates the prevailing conditions of a country (developed, emerging or developing) in order to support its innovation endeavours (OECD, 2012). Therefore, in the latest draft white paper on science, technology and innovation, the government has made extensive changes to its NIS in response to a number of challenges and opportunities (DST, 2018a). According to DST (2018a) the changes are meant to create an NSI that can boost creativity, learning and entrepreneurship in South Africa. These three important concepts and others related to them form part of the capability building blocks for innovation in South Africa and thus are discussed in this subsection.

Creativity

Okpara (2007) describes creativity as “the ability to make or bring into existence something new, which may be a new solution to a problem, a new method or device, or a new artistic object, etc”. Other scholars consider creativity as the “construction of ideas or products which are new and potentially useful” (Amabile, 1988; Fillis & Rentschler, 2010); and doubtlessly, creativity is the starting point for innovation (Okpara, 2007). The concept of creativity is in line with some of the functions of the national research and development strategy of South Africa (see **Section 4.2.1**).

Learning and human resource development

The second element that has been stressed in the draft paper is learning. In simple terms, learning is the “collection, imparting, interpretation and storage of knowledge”(Vidic, 2013). However, it is noted by many scholars of learning theories that the “fundamental condition for successful development and gaining of competencies is the existence of high-quality and efficient learning system implemented by well qualified personnel” (Vidic, 2013). Moagi (2002) also states that “innovation needs people – well-trained, effective scientists, engineers and technologists”. The OECD (2001) also acknowledges the benefits obtained from investing in human capital which include the generation of private and social benefits, and most importantly the significant role human capital plays in economic growth. There is no doubt this explains why the latest draft white paper emphasizes learning as an important element of NIS (DST, 2018a).

Unfortunately, as can be seen from **Table 4.4** in **Chapter 4**, there is just a marginal rise in the number of pupils who either sit and/or even obtain a bachelor’s pass in the past 10 years. However, there is a dire need for South Africa to accelerate the supply of skills so as to improve productivity, social and economic outcomes for individuals and communities (Mkhize, 2017).

Over the years, South Africa has developed a number of interventions to promote the development of human resource for various skills. As a result, there is a reasonable improvement in the number of scientists, engineers and technologists produced since the introduction of the South African national research and development strategy. For example, a report by a Statistics South Africa of 2017 showed that university graduation numbers were on the rise (Mkhize, 2017). Furthermore, **Table 4.6** in **Chapter 4** shows that there is a trajectory growth in the number of masters and PhD trained graduates.

Most importantly, according to DHET (2019a), in the period between 1994 and 2017, the number of student enrolments in universities more than doubled from 495 356 in 1994 to 1 036 984 in 2017, while the enrolments in TVET colleges also more than doubled from 357 885 in 1999 to 688 028 in 2017 (refer to **Table 4.5** in **Chapter 4**). Unfortunately, enrolments in community education and training (CET) colleges, declined from 294 855 in 1999 to 258 199 in 2017 (DHET, 2019a).

The SARChI programme whose one of its key objectives is to expand the scientific research and innovation capacity of South Africa has awarded 150 Research Chairs to 21 public universities across the country in open and directed categories since its inception in 2006 (NRF, 2018a). This is quite significant as the initiative attempts to build a critical mass of supervisory capacity, equipment, researchers and students (NRF, 2018b)

Another strategy initiated by South Africa that is aimed at improving the impact of the skills challenges in the country is the human resource development strategy in South Africa (HRD-SA) for 2010-2030. According to HRD-SA (2009) the human resource development policy framework "focuses on areas that significantly and positively impact on South Africa's economic performance such as (1) educational attainment, (2) skills development, (3) science and innovation, and (4) labour market/employment policies".

Entrepreneurship

Another element emphasised in the draft white paper in the NIS policy is entrepreneurship, and the OECD (1999) considers it as a function of the NIS. This study adopted the definition of entrepreneurship according to Kao (1993), namely, "entrepreneurship is the process of doing something new and something different for the purpose of creating wealth for the individual and adding value to society" (as discussed in **Chapter 4**).

Entrepreneurship is considered a key priority area by many developing countries including South Africa with the unparalleled capacity to positively assist in the creation of jobs and wealth in an innovative and independent way (Okpara, 2007). No wonder, the new draft policy emphasises the importance of entrepreneurship. In fact, the general attitude by the South African government towards entrepreneurship is very positive. For example, the South African government established the Department of Small Business Development (DSBD) in 2014 whose main focus is “to support small business and cooperatives, with an emphasis on programmes that advance entrepreneurship amongst women, the youth, and people with disabilities with the view of contributing to job creation and economic growth”(DSBD, 2019). Indeed, South Africa is seriously following the general strategies for promoting entrepreneurship outlined in **Table 4.8** of **Chapter 4**.

To reiterate the importance of entrepreneurship, over a decade ago, South Africa had made very little strides to improve its economic outlook particularly with respect to black economic empowerment (Francke & Alexander, 2019; Naidoo, 2002). However, according to GEDI (2017), South Africa is now, by far, an entrepreneurial frontrunner in sub-Saharan Africa. The country has made remarkable developments to get rid of structural factors and it has given the institutional support necessary for high-growth businesses to emerge and thrive. In addition, the government has developed progressive policies that are specifically designed to close historical gaps. As a result, South Africa now produces some of the most innovative and successful enterprises on the continent (GEDI, 2017). With the addition of targeted and coordinated policies that are meant to address the remaining bottlenecks, there is no doubt the country is poised to achieve greater growth through entrepreneurship. As already stated, South Africa is seriously following the general strategies for promoting entrepreneurship outlined in **Table 4.8** of **Chapter 4**.

In view of the results achieved by the government, undoubtedly a number of government strategies pertaining to technology and innovation policy has made positive strides in enhancing technological and economic wellbeing of the country.

5.2.2 Financing R&D: discussion

One important capability building strategy highlighted in **Chapter 4** is the financing of R&D. The funding of R&D has always been debated globally by various NIS actors in numerous forums. As can be seen from **Table 4.1,** South Africa’s expenditure on R&D is in the range of 0.7-0.8% of GDP whereas the other BRICS countries apart from

India are above 1% of GDP with China spending more than 2% of GDP since 2014. Despite showing less expenditure in terms of percentage of GDP, the South African government's national development plan (NDP) is explicit on the necessity of increased investment in scientific and technological activities with a view of enhancing economic growth and development (DST, 2015). **Figure 5.1** obtained from DST (2015) shows how government funding for various scientific and technological activities is disbursed in South Africa. As can be seen from the figure, a number of instruments have been employed by the government for funding scientific and technological activities in the country, e.g., tax incentives, grants, bursaries, scholarships, etc, (DST, 2015). In a study by Ebersberger (2005) on public R&D funding in Finland it was found that "grants and tax incentives for innovation activities not only attempt to mitigate against underinvestment in R&D (which has a clear focus on innovation input), but also try to influence innovation output and outcome".

5.2.3 Performing R&D: discussion

A number of publicly-funded institutions (**Table 4.3**) as well as public universities are aggressively involved in research activities. Some private firms are also directly and/or indirectly involved in R&D. The focus of research in South Africa is broad and covers various key and strategic areas as specified by NRF (2014) in the evaluation and rating document. **Table 5.1** gives the key research areas as specified by NRF (2014).

The Department of Higher Education and Training also evaluates research outputs of South African universities and other research institutes according to the research outputs policy of 2015 (DHET, 2015). In such yearly evaluations of research outputs, the DHET (2019b) also categorises the research publication outputs by the classification of education subject matter (CESM) which was published in 2008 after a review of the old 1982 classification (DoE, 2008). The results show that South Africa is engaged in broad, but internationally recognised research areas which is very encouraging (DHET, 2019b).

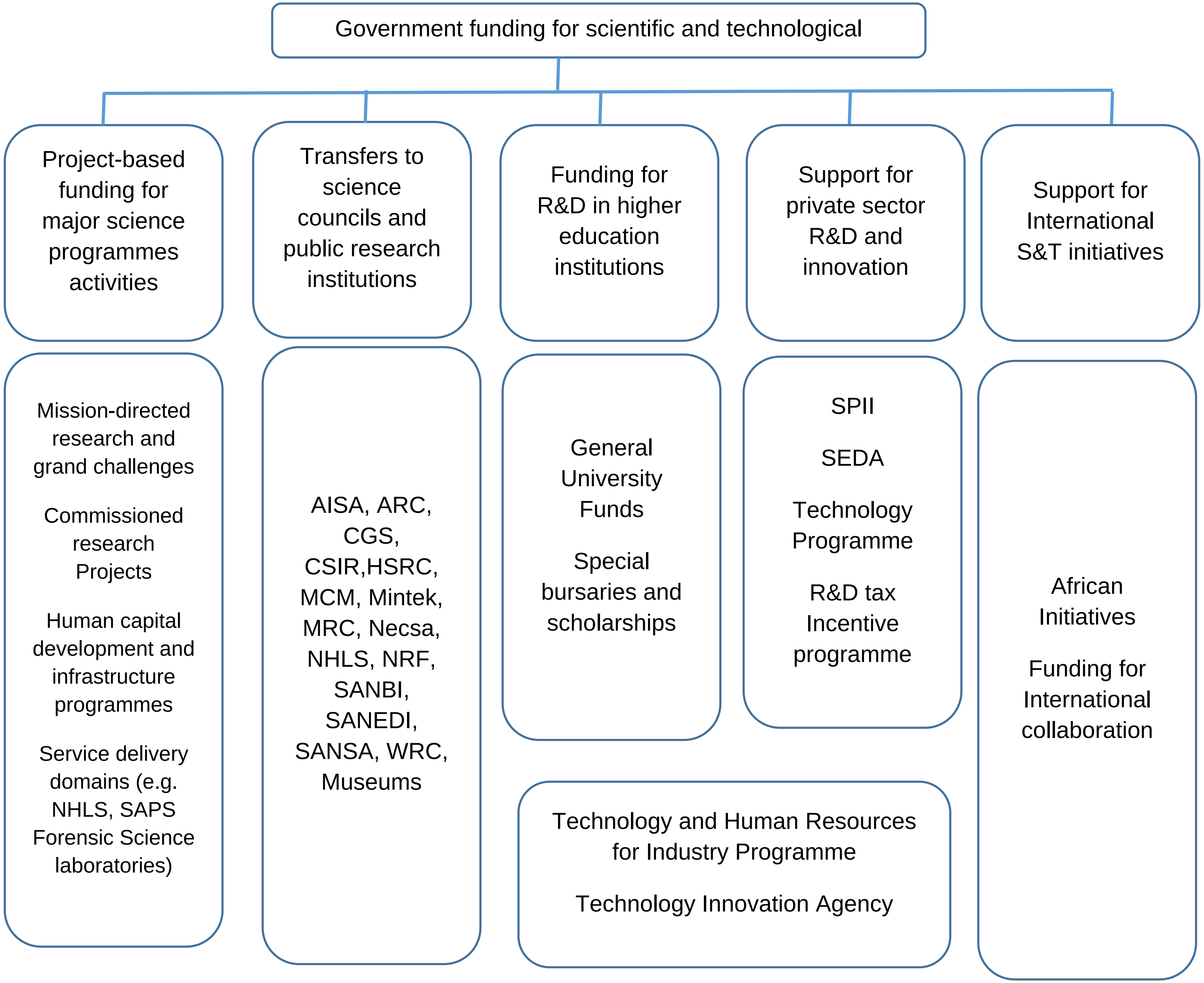

Figure 5.1. Disbursement of government funds to scientific and technological activities (DST, 2015)

A study by Okagbue et al. (2018) compared the research outputs of universities of technologies in Nigeria to other countries including South Africa based on 27 subject areas from Scopus. The results of Okagbue et al. (2018) shows that the scope of South African research even at international level is quite broad. It is also noteworthy that there is a lot of potential overlaps in many areas of research in South Africa (NRF, 2014). Furthermore, the various main areas of research as given in **Table 5.1** which South African researchers are involved in, particularly the overlaps, could be explored further for collaboration and/or establishment of multi-disciplinary teams.

Table 5.1. Key research areas in South Africa (NRF, 2014)

S/No.	Key research area
1	Animal and Veterinary Sciences
2	Anthropology, Development Studies, Geography, Sociology and Social Work
3	Biochemistry, Molecular and Cell Biology
4	Chemistry
5	Communication, Media Studies, Library and Information Sciences
6	Earth Sciences
7	Economics, Management, Administration and Accounting
8	Education
9	Engineering
10	Health Sciences
11	Historical Studies
12	Information Technology
13	Law
14	Literary Studies, Language and Linguistics
15	Mathematical Sciences
16	Basic and Applied Microbiology
17	Performing and Creative Arts, and Design
18	Physics
19	Plant Sciences
20	Political Studies and Philosophy
21	Psychology
22	Religious Studies and Theology

5.2.4 Technology diffusion: discussion

As already discussed in **Chapter 4** as well as according to Jaffe (2015), technology diffusion is the process by which new technologies are adopted so that they are utilised in firms, households and many other sectors in either a given market or across different markets. As stated also in **Chapter 4**, technology diffusion is also a function of the NIS and a means of transferring knowledge (OECD, 1997, 1999). It must be noted, however, that technology diffusion is not instantaneous and, indeed, the variability in the diffusion rate is quite enormous (Jaffe, 2015). **Table 4.7** in **Chapter 4** is a good illustration of the differences in the rate of diffusion even within similar industrial areas.

Certainly, as can be seen from **Table 4.7**, technologies in the same discipline (energy sector) vary in both technology readiness level and time for deployment. According to Cloete et al. (2014), “technology readiness level assesses the maturity of a technology and can guide decision-making. Nine levels are defined, commencing with the lowest level (TRL 1), where the transition from scientific research is just beginning, to the highest level (TRL 9), where the technology has been thoroughly tested and has been successful in the operational environment”.

Several research studies have also shown that technological diffusion usually follows an S-shaped pattern (Jaffe, 2015; Manuelli & Seshadri, 2003; Rao & Kishore, 2010) and may take a substantial amount of time, as alluded to already, from 15-30 years after discovery for 10% to 90% of such a process and /or technology to be adopted by the production unit and/or the society (Grübler, 1991; Jovanovic & Lach, 1997; Manuelli & Seshadri, 2003). According to Jaffe (2015), the S-shaped technology diffusion pattern occurs as follows: “initially, only a few early adopters try a new technology. At this early stage, both the fraction of potential users who are using the new technology and the rate of increase of that fraction are low. Gradually, both the extent of use and the rate of increase of that extent rise, leading to a take-off phase in which diffusion accelerates significantly. At some point, the extent of use becomes high and the rate of increase of that extent falls, leading to a levelling off or saturation. Depending on the technology, saturation may occur at 100% of potential users or close to it, or at some lower level”.

It must also be noted that different factors impede and/or affect the rate of technology diffusion. Firstly, the economic aspect, according to Jaffe (2015) implies that “on the demand side potential adopters such as firms and individuals respond to the economic benefits of the new technology relative to its alternatives. On the supply side, firms respond to the profitability of selling the new product”. Research studies have also shown that information and information processing is also very important in technology diffusion. For example, Jaffe (2015) states that “what potential adopters know or do not know about the new technology, and by their ability to process that information affect adoption decisions. In addition, the act of adoption and subsequent use by one actor may create a source of information about the new technology for other actors". Finally, history or culture or institutions many also affect the diffusion of technology. According to Jaffe (2015) "social and cultural norms and habits may affect people's decisions to use a technology. In addition, an existing technology may be embedded in institutions and physical infrastructure in ways that advantage it over the new technology, so that these advantages then have to be overcome for new technology adoption to occur".

However, more recently, the diffusion of technology across the globe has accelerated over time (WorldBank, 2008), particularly in countries that are open to international trade and investment (Perkins & Neumayer, 2005). Unfortunately, most of the developing countries, except a few, are still relying mainly on the diffusion of technologies from the developed countries (WorldBank, 2008). The exceptional countries normally adapted the acquired advanced technologies to their own local conditions, which in many cases, require some form of innovation (WorldBank, 2008).

5.2.5 Joint industry activities: discussion

There is no doubt that partnering and collaborations between and amongst various industries can significantly improve their economic performance. For example, a report by Deloitte (2012) says "South African companies need to explore collaborative opportunities with government, academic institutions and companies in other industries in order to improve the country's competitiveness, explore new markets and lower costs to consumers". **Table 4.9** in **Chapter 4** gives selected examples of companies in South Africa and the nature of their collaborations. As indicated in **Table 5.2**, the benefits of collaborations by businesses fall under several categories, and there is no doubt South African companies can benefit immensely from all categories.

Collaboration in the construction industry, in particular, is quite vital. The industry is embroiled in a number of problems with "fragmentation being considered as the root cause of many problems in the industry" (Cain, 2003; Dainty et al., 2001; Emuze & Smallwood, 2014; Harding, 2010). Dulaimi et al. (2007) as well as Emuze and Smallwood (2014) mention a number of benefits of collaborations in the construction industry including "improved working relationships, effective information exchange, less conflicts and risks, higher productivity, cost savings, improved quality, faster processes and better customer responsiveness". Such benefits are applicable to South Africa, in particular, and other countries, in general.

Table 5.2. Key benefits of business collaboration (Nibusinessinfo, 2019)

Benefit	Example
Financial benefits	The potential to uplift the sale of goods domestically or internationally; ability to apply for contractual jobs that are larger or sharing various resources so as to minimise costs
Growth of the base for human capital	The potential to grow employees' expertise and competences; prevent job losses and maximise employment creation; and encourage the motivation of members of staff
Development of physical capital	The capability to have and share important common facilities, required resources, raw materials and latest equipment
Development of intellectual capital	The ability to make use of combined skills, practical or theoretical knowledge and capabilities

The importance of collaboration has also been emphasised by Giesen et al. (2010) in the area where new and distinctive concepts that are capable of supporting the financial viability of an organization are developed and utilised (i.e., business model innovation). Giesen et al. (2010) states that firms "need to orchestrate customers, partners, and suppliers through collaboration and partnership models". A study by IBM (2008) over a decade ago showed that 85% of the CEOs consider collaboration and partnerships as very important global strategic elements for innovation. In nanotechnology, in particular, DST (2005) also states that "collaboration among traditional disciplines, research teams and institutions is critical for both progress in understanding nanoscale phenomena and developing nanotechnology applications".

5.2.6 Public/private interactions: discussion

Table 4.10 shows some of the outputs that emerged from university-industry collaborations. The discussion of **Table 4.10** given herein summarises the analysis given by HESA (2012). It is noted from the table that classic outputs of academic nature such as 'graduation of candidates with the right expertise and principles', publications of research articles or writing of dissertations (or thesis) were mostly reported in all academic engagements with the firms involved. There is no doubt that graduates with the right skills and values are quite important in view of the fact that it is one of the government strategies with respect to human resource development policy (DHET, 2009). Certainly, academic publications or dissertations are a manifestation of the country's scientific productivity.

The table also shows that typical firm outputs, such as new or improved products and processes, were least frequent which implies that there is less focus on technological performance in the collaborations. This finding is quite worrying for South Africa as it is well known that the role of technological performance, as measured through patents in this study, is vital because it enables a company to add value to its products and processes, and thus has a significant impact on the innovation process (Hao & Yu, 2011). Ideally, Hao and Yu (2011) state that technological performance or technological capabilities "help the firm (or country) to build competitive advantage through making more competitive products and services and more effective processes, or creating completely new business". Therefore, it is imperative that public/private interactions engage in applied research where new or improved products and processes are realised.

For comparison purposes, and as a follow-up from the previous paragraph, HESA (2012) states that "new or improved processes were more frequently reported than new products or scientific discoveries, which illustrates the nature of university involvement in firm innovation processes. Spin-off companies were also more commonly reported as an output of interaction with MNEs, which is more than likely related to the lack of venture capital in South Africa, and the need to access larger global markets".

As stated by HESA (2012) "graduates with the right skills and values" was the most frequently reported output for both large SA firms and SMMEs, while for MNEs, academic collaboration was the most common result of the collaborations. This might suggest that the types of outputs from academic engagement with firm partners are more beneficial to academic institutions and academics than they are for firm partners. Definitely, one of the reasons and/or motivation by academics for such a trend is that academics get subsidies from government when they publish (research publications) or graduate postgraduates through dissertations and theses (DHET, 2015, 2019b). The most common output that is not traditionally academic was reports or popular publications, which are closely aligned with extending and applying academic expertise". For example, the involvement of the University of the Witwatersrand's academics in policy formulations using their research experience is one of the university's 2018-2022's strategic plan for research (Wits, 2019).

The contributions of universities through collaborations with industries to technological innovation can also occur in many other different forms including (1) the performance of research in technological fields that are relevant to industry, (2) provision of technical assistance to industries in areas that need expertise, (3) educating and training of professionals at academic institutions, and (3) supporting academic staff to engage themselves in consulting and commercialization activities that are beneficial to industries (Geiger & Sá, 2008; Sá, 2015).

In South Africa, an important funding scheme that is aimed at incentivizing advancement in technology and innovation activities by promoting the collaboration between companies, academic institutions and publicly owned science councils is called THRIP (an acronym for technology for human resources and innovation programme) (HESA, 2012). THRIP was set-up in order to promote research, human resource capacity and technology outputs in science, technology and engineering fields, so as to improve the competitiveness of South African industry (HESA, 2012).

5.2.7 Personnel mobility: discussion

South Africa has signed multitudes of bilateral agreements/MoU with a number of countries for various reasons. **Table 4.11** of **Chapter 4** gives an outline of a selected number of South African bilateral agreements and/or MoUs with other countries. The forms of cooperation include amongst several others the following: (1) carrying out visits on an exchange basis by researchers, experts and scholars; organizing technical related training, seminars or study tours on subjects of mutual interest; doing publicity and public education activities together (SA/China, 2000), (2) giving golden lifetime opportunities to researchers to meet and interact (SA/Japan, 2003), (3) joint organisation of seminars, workshops and meetings with the participation of scientists, experts, regulators, legislators and stakeholders; visits of delegations and experts from the two countries (SA/Mozambique, 2014), (4) to facilitate and allow clinical staff from England and the healthcare personnel in the Republic of South Africa to work together. The main emphasis is the rural areas where the collaboration is meant to ease the access to universities, colleges and schools of training for the health professionals during various programmes including scientific research studies; specific training of health professionals; (c) training of postgraduates; (d) visits pertaining to studies (SA/UK, 2003), (5) promoting the participation in international conferences, seminars and other relevant events on competition issues organised by BRICS international competition conference (SA/BRICS, 2016), and (6) promoting collaborations among the BRICs nations through education, science and culture (BRICS, 2015)

As can be seen, personal mobility between South Africa and other countries for research related activities, for example, is prominent and is quite relevant in the context of this particular study. For example, it is a well-established fact by many scholars that personal mobility is linked to the outcomes of innovation by engineers and scientists (Choudhury, 2017; Singh & Agrawal, 2009; Stevens, 1997). Most importantly for South Africa, the movement of human resources to other countries and vice versa in the context of the bilateral agreements/MoUs is significant to the emerging knowledge economy (Pogue, 2007). Moreover, OECD (1997) states that "the movement of people and the knowledge they carry with them (often termed "tacit knowledge") is a key flow in NIS".

5.3 Discussion of capability building strategies for nanotechnology in South Africa

This section discusses the results given in **Chapter 4** pertaining to capability building strategies and/or policies for nanotechnology in South Africa. Such strategies and/or policies are aimed at leveraging the inherent capabilities and/or applications of nanotechnology in a wide spectrum of industries so as to enhance technological and economic catch-up by South Africa.

5.3.1 Locating the nanotechnology strategy in the South African strategy landscape: Discussion

It is generally agreed by scholars globally that nanotechnology is a general purpose technology (Graham & Iacopetta, 2014; Kreuchauff & Teichert, 2014; OECD, 2010; Shea et al., 2011; Soldatenko, A, 2011) whose innovations can be included in a variety of applications (Kreuchauff & Teichert, 2014). The application and/or use of nanotechnology in a wide range of areas and industries is one of the three attributes of general purpose technologies as already discussed in **Subsection 2.7.1** (Elhanan, 1998; Lipsey et al., 2005). Certainly, many studies have strongly emphasized that nanotechnology has found widespread applications in various areas including water treatment, medical, automobile, food and packaging, cosmetics and sunscreens, building and construction, electronics and computing, clothing and textile, personal care and health, etc (Nielsen, 2008; Salamanca-Buentello et al., 2005; Soldatenko, Alexandrina, 2011). **Table 2.5** in **Chapter 2** also gives an outline of a number of applications of nanotechnology which are specifically important for developing countries. Therefore, in view of nanotechnology's myriad applications in a number of sectors, placing it within other national strategies as stated in **Subsection 4.2.2** is imperative.

5.3.2 Public funding: discussion

As discussed earlier the applications of nanotechnology encompasses almost all spheres that matter in many economic sectors. Therefore, nanotechnology being an interdisciplinary field, it is expected that various organizations/ministries/agencies of government and the private sector would be involved in funding it (Ezema, I. C. et al., 2014). Musee et al. (2010) argues that the existing models of funding of nanotechnology are concentrated on the fundamental investigations and the application of the field. Musee et al. (2010)'s view is that research should also focus on research of the risk aspects of nanotechnology. Nevertheless, by 2010, following the national nanotechnology strategy of 2005, the South African government had invested over R170 million in different aspects of nanotechnology R&D (DST, 2006; Musee et al., 2010).

One of the focus of national nanotechnology strategy is conception, matching research offerings with industrial manufacturing and processing capacity, commercialisation, and incubation of new nanotechnology-based industries and the transfer of new technologies to existing industries (DST, 2005). As a result, according to CSIR (2015), "over the last few years the CSIR has pumped tens of millions of Rands into using nanotechnology to make South African industries like cosmetics and plastics more competitive". Furthermore the government also offers a number of incentives (e.g., grants, tax rebates, etc) that are mainly aimed at new equipment and facilities for basic research rather than technology development itself (DTI, 2015). Other types of funding by the government with respect to nanotechnology are discussed in other sections.

5.3.3 National nanotechnology equipment programme: discussion

Research equipment, in particular, and research infrastructure, in general, used by researchers to conduct cutting edge research for the generation of knowledge which promote innovation for the economic development of a country is vital. The South African government recognises the importance of equipment in nanotechnology hence the introduction of the national nanotechnology equipment programme (NNEP) in 2005 (NRF, 2015). The NNEP resonates well with the national nanotechnology strategy meant to "establish and maintain geographically distributed multi-user facilities to provide researchers with advanced instruments for design, synthesis, characterisation, modelling and fabrication" (DST, 2005). Ideally, the NNEP was providing ring-fenced grants to researchers through the NRF to purchase nanotechnology-related research equipment (Makhoba & Pouris, 2017; NRF, 2015). The NNEP came to an end in 2015 after an investment of over R400 million nanotechnology-related research facilities (Dube & Ebrahim, 2017).

5.3.4 Nanotechnology innovation centres: discussion

The two nanotechnology innovation centres at Mintek and CSIR are national organisations established by DST (Chidanyika, 2016; DST, 2008) with a focus on national nanotechnology strategy as well as the national R&D strategy (Mintek, 2019). Their main mandate is to commercialise nanotechnology-enabled products that are directed at seeking solutions that address challenges facing South African societies (CSIR, 2017).

The centres have proudly embarked on innovative research on nanostructured materials and formed substantial collaborative research with both local and international research institutions (CSIR, 2017). Amongst the centres' many other achievements include "a prototype breath analyser for detecting diabetes without the need of a blood test; setting up of the water and catalysis research groups as new research areas in nano; the polymer processing laboratory for testing and evaluation of industrial samples; and the development and establishment of the nanomaterials industrial development facility (NIDF) in 2015" (CSIR, 2017). According to CSIR (2017), "the NIDF enables industry, research entities and small, medium and micro enterprises (SMMEs) to develop and scale up high-tech nanotechnology-enabled materials".

Furthermore, the nanotechnology innovation centre at Mintek "has embarked on the development and manufacturing of low-cost rapid diagnostic devices, biosensors and other electronic devices in health; the development of water treatment devices and systems and the beneficiation of minerals, contributing towards job creation and economic development"(Mintek, 2018). The devices for health and water treatment are directly linked to the social development cluster of the national nanotechnology strategy (DST, 2005).

5.3.5 Human capital development: discussion

Since the inception of the national nanotechnology strategy in 2005, South Africa has played a pioneering role in promoting human resource development in nanotechnology. As shown in **Table 4.12**, a handful of higher education institutions are training postgraduates on a DST funded two-year Master's degree program leading to an MSc in nanoscience qualification (Dube & Ebrahim, 2017) which started in 2012 (Khoza, 2018). Basically, such DST initiatives (student support programmes) advance the development of human capital by fast-tracking high-end skills development in nanoscience and nanotechnology (DST, 2008). According to Khoza (2018) "from 2012 to 2016, a total of 135 students have been admitted to the programme; and from 2012 up to March/April 2018 about 133 students have graduated from the programme". There is no doubt that the Master's degree program has contributed to the production of masters' degree graduates in the country and created an interesting career pathways for qualified youth in South Africa.

Most importantly, most of South Africa's publicly owned universities and research councils such as CSIR and Mintek are vigorously involved in R&D pertaining to nanoscience and nanotechnology thus providing hands-on training, education and skills development to researchers and professionals.

Furthermore, as part of the DST's research-chairs initiative (SARChI), targeted research chairs in the field of nanotechnology have been established (DST, 2008) as shown in **Table 4.13** of **Chapter 4**. Amongst their objectives, the research chairs focus on increasing the level of research activity in the field, thus contributing significantly to the development of human capital in nanotechnology by producing high-quality postgraduate students (Khoza, 2018).

The 10 year plan on nanoscience and nanotechnology also emphasizes that “the bilateral and multilateral collaborations on nanotechnology, such as the India-Brazil-South Africa forum (IBSA), South Africa-France, and South Africa-Argentina collaborations, will be exploited for the development of expertise and skills training in the identified research areas” (DST, 2008).

In addition to the already discussed achievements, according to de Groenendaal (2018), “the investment in the flagship projects of the national nanotechnology strategy has yielded considerable outputs; for example, by 2015, 464 postgraduate students had been trained, 92 postdoctoral fellows supported, 326 collaborations established, 352 articles published in highly cited journals, 80 conference proceedings recorded and 17 patents registered”.

5.3.6 DST-NRF centre of excellence in strong materials: discussion

A review of the CoE-SM’s performance in 2009 by a team of experts from various institutions found the centre’s performance to be exemplary and that it had achieved its objectives (Malherbe et al., 2009). Another review in 2013 that looked at CoE programme as a whole comprising of nine centres was “most impressed with the performance of all the centres in terms of their outputs and their achievements in networking researchers” (Bawa et al., 2013). From **Table 4.14** in **Chapter 4** it is clear that, with a host of more than 50 researchers, the CoE-SM acted as a network that brought researchers together to tackle projects that are both locally and internationally relevant. It is also noted from **Table 4.14** that the CoE-SM produced a reasonable number of patents which shows that it is engaged in research that is relevant to industry. In a review report, Malherbe et al. (2009) also states that the “synergy between basic research and applied (industrial) research is one of the main positive features of CoE-SM”. The CoE-SM is also impressive in its production of research through publications (more than 660 research papers), and recruitment of postgraduate students (more than 60 every year) and graduation of postgraduate students (over 180 graduates from its inception). This shows that the centre has been involved in the pursuit of research of exceptional quality and in the education and training of postgraduate students which is a vital aspect of human capacity development in South Africa.

5.4 Technological catch-up in water treatment and medical related nanotechnology-based processes and/or products

This section deals with a wide range of activities that are related to scientific and technological performance of a firm or country, namely publications, patents and citations. Other aspects that may enhance scientific and technological performance with respect to water treatment and nanomedicine are also discussed.

5.4.1 Technological catch-up in water treatment

Publications in water treatment: Discussion

As stated already in **Section 2.8** and **Subsection 4.3.1** the publication of peer-reviewed scientific research articles is considered as an indicator of a nation's scientific performance (Carpenter et al., 2014; Sargent Jr, 2016). In terms of contributions to the total number of publications, **Figure 4.1** shows that the USA (40.9%) is the leader followed by China (28.7%) and India (20.5%) in the nine year period. Brazil, South Africa and Russia are the lowest performers scientifically. **Figure 4.2** which is based on a year-by-year publications basis shows that the USA continued to be the leader from 2010 to 2016 whilst other countries have had fluctuations, particularly China and India which exchanged leadership from 2012 to 2016. It is not surprising that the USA had been the leader in nanotechnology, in general, and nanotechnology-enabled water and waste treatment publications, in particular, because the NNI (refer to **Subsection 2.7.2**) in the USA has made major global impact and led to other countries investing in nanotechnology research as well (Bhattacharya & Bhati, 2011).

As can be seen from **Figure 4.2**, after 2016 China started leading the USA and India in terms of scientific publications of nanotechnology-enabled water and wastewater treatment publications. This is not surprising because a study by Bhattacharya and Bhati (2011) showed that China surpassed the USA in nanotechnology publications in 2009. As far back as the 1980s China had realised the important role of nanotechnology and thus the government developed policies to support the area which has led to heavy investment in nanotechnology (Liu & Zhang, 2007; Zhang et al., 2017; Zhao et al., 2008), and China is the fastest nanotechnology growing market in the world (Bhattacharya & Bhati, 2011). Moreover, China's national nanotechnology strategy emphasizes the importance of basic science and there is strong financial support from government (Huang & Wu, 2012).

In general, according to Veugelers (2017) “Chinese R&D investment in science and technology has grown remarkably, with the rate of growth greatly exceeding those of the United States and the European Union”. Moreover, China has also “established some large-scale comprehensive scientific research institutions” (Wu & Fan, 2010). South Africa’s publications started going up from 2016 whilst that of Russia has continued to slow downward since 2017.

Citations of the publications in water treatment: Discussion

The importance of citations has been well articulated in **Subsection 4.3.1**. It has a strong link to the quality of scientific research output (Aksnes et al., 2019). **Figure 4.3** clearly shows that the USA is way above all the BRICS countries in terms of citation based on the data captured via the Web of Science in this study. Following the USA in second, third, fourth and fifth place are India, China, Brazil and South Africa, respectively. A similar trend was also obtained by Sargent Jr (2016) in a study that compared the USA, Germany, other EU nations (combined), Japan, China and South Korea. A study by Bhattacharya and Bhati (2011) showed that despite China having a number of scientific papers in nanotechnology, in general, its citation record is still lower than the USA.

The trend in which the USA is leader in the citation of research particles may not be long before China takes the lead in citations as the government continues to invest heavily on nanotechnology. For example, China’s national nanotechnology strategy argues that “successful nanotechnology development depends on basic science, strong funding, competent R&D personnel and highlights the need for training and retaining scientists in the field” (Huang & Wu, 2012).

Citations of South African research papers in nanotechnology based water and wastewater treatment on a year-by-year basis from 2010 to date is the lowest. This may be attributed to the low visibility (fewer scientific publications) of South African research and/or the lack of quality in the scientific research papers. However, according to Van Noorden (2017) “lack of citation cannot be interpreted as meaning that articles are useless or valueless”.

Collaborations amongst countries in the publications in water treatment: Discussion

According to Groboljšek et al. (2014) “collaboration is becoming one of the most significant features of scientific and technological activities in the 21st century and has become one of the most important forms of knowledge production since World War II”. The OECD (1997) considers technical collaborations in addition to informal interactions amongst industries as one of the most significant ways in which knowledge is transmitted in NIS. Following the definition by the OECD (1997), this study categorised collaboration as a capability building block for innovation (see **Subsection 4.2.1**).

From **Table 4.15**, there is strong evidence to support the proposition that collaboration plays an important part in scientific research publications in nanotechnology-enabled water and waste water treatment. For example, 92.3% (12 out of 13) of South Africa’s publications are generated via collaborations. For South Africa, though it shows that the country is collaborating with other countries, the trend also indicates that South Africa’s own capability building strategies (e.g., funding, human resource development, etc) in the area is weak and/or is not working.

Surprisingly, the BRICS nations despite having several MoUs have negligible collaboration results amongst themselves. This may be attributed to the fact that research studies take long to generate tangible results. In fact, the BRICs is a new organisation such that significant research that produce benefits emanating from the group is still limited despite a significant number of MoUs, and, moreover, much research time is needed to fully explore its overall scientific relevance and thus be published.

Disciplines and/or research areas in the publications in water treatment: discussion

A lot of scholars in the field of nanotechnology acknowledge that it is a multidisciplinary and interdisciplinary field (Kumar, 2014; Liu & Zhang, 2007; Zhao et al., 2008). Zhao et al. (2008) states that “nanotechnology is far beyond the traditional concepts of the classic scientific or industrial disciplines; it completely fuses disciplines as diverse as physics, chemistry, materials science, biology, medicine, cognitive sciences, informatics, engineering, computer simulation, industry, agriculture, environmental sciences, etc". There is no doubt that **Figure 4.4** is a clear evidence that nanotechnology research in water and wastewater treatment in South Africa is multidisciplinary which confirms the belief of several scholars such as Liu and Zhang (2007), Zhao et al. (2008) and Kumar (2014) that nanotechnology crosses the boundaries of various traditional academic disciplines.

Patents in water treatment: Discussion

According to the OECD (2004) "patents play an increasingly important role in innovation and economic performance". As discussed in **Section 2.8**, despite being legal documents, patents are also considered as a paper trail of technology advancement (Huang et al., 2011). **Figure 4.5** clearly shows that the USA is way ahead of all other states in the study. China comes in second position and Russia and India are in third and fourth positions, respectively, in the filing of patents through WIPO. From the data accessed via WIPO, South Africa produced no patents related to nanotechnology-enabled water and wastewater treatment in the 2010-2018 period. As stated in **Subsection 4.3.2**, not all inventions are patented due to industrial secrecy and some inventions are not technically patentable (Archibugi, 1992; Arundel, 2001; Fontana et al., 2013). These could be some of the reasons why South Africa may not have patented in the nine year period studied. However, from **Table 4.16**, it is seen that South Africa filed about 20 patents through WIPO before 2010.

One other observation from both **Figure 4.5** and **Table 4.16** is that though China and India have high publication rates (see **Figure 4.2**), their patenting activities are quite limited compared to the USA. However, in recent past, China's patent applications and approvals have grown significantly high in many other fields (Long & Wang, 2019). In fact, China surpassed the USA and Japan in 2011 in terms of patent applications (Long & Wang, 2019). According to Long and Wang (2019) an increase in the number of patents by China is due to the "patent promotion policies (PPPs), which are measures adopted by various government agencies linking tax incentives and subsidies to patent ownership, have significantly contributed to the rapid growth in both patent applications and patent approvals in China". Nevertheless, the adoption of PPPs has also resulted in a decrease in the quality of patents (Long & Wang, 2019).

Amongst the BRICS states South Africa and Brazil have generated none and/or produced the least patents in both **Figure 4.5** and **Table 4.16** in the nine year period. According to OECD (2009) some of the reasons that may inhibit patenting and/ or opposition to filing of the patent include “the patent’s subject matter is not patentable; the patent does not disclose the invention clearly and completely; or the patent’s subject matter extends beyond the content of the application as filed”.

Unfortunately, Warner (2014) states that “many patents are never developed into actual products or innovations possibly because of the lack of necessary production facilities or for strategic reasons”. In addition, some patents are technologically or economically worthless (Warner, 2014) and thus are not attractive to investors.

Top 10 applicants for patents in water treatment: Discussion

Steady and safe supply of water requires the support of a sustainable water treatment technological development (Fujii & Managi, 2017). This section discusses firms and/or individuals whose patents were granted through WIPO in nano-based water treatment innovations. **Table 4.17** shows that all the top 10 patent applicants by the USA are either firms or universities. Apart from patent applications from firms and/or universities, the rest of the other countries had also individual patent applicants, i.e., Russia (4), India (5), China (2) and South Africa (5). Brazil had only three applicants from firms and/or universities in the period 2010-2018. The number of firms patenting in the USA is not surprising because the country is a world leader in corporate nanotechnology spending according to Flynn et al. (2013).

5.4.2 Technological catch-up in medical fields

Publications in medical fields: Discussion

The medical industry is an important entity in a country that strives to improve the health of its citizens. According to WHO (2008) the health industry through the health of the citizens of a country makes an important contribution to economic progress. On the other hand, it is well recognised that research in medicine is a cornerstone for safe, effective, efficient, and patient-centred delivery of health care globally (Kumar, 2010); and there is no doubt research in any form does not occur in a vacuum, but relies significantly on scientific and academic innovation (Young, 2015).

Figure 4.6 shows that the contribution of the USA to scientific research in the field of medicine related to nanomaterials is very high. However, as can be seen from **Figure 4.7**, China is closing the gap towards the USA and it is possible that within the next year (or so) China will surpass the USA. South Africa has the lowest contribution amongst the countries and even within the BRICS countries in a nine year period. Though South Africa has fewer publications in the field of medicine related to nanotechnology compared to other nations in the study, it is acknowledged by Dube and Ebrahim (2017) that "South Africa is one of the countries engaged in nanomedicine research and product development on the African continent". Saidi et al. (2018) also states that "since 2005, South Africa has invested in research on nanomedicine focusing on pro-poor initiatives which prioritise diseases such as HIV/AIDS, malaria and tuberculosis". In addition, in the national nanotechnology strategy the government had earmarked NNEP through NRF for the purchase of nanotechnology-related research equipment (Makhoba & Pouris, 2017; NRF, 2015).

Citations of the publications in medical fields: Discussion

There is no doubt that the significance and /or attention given to scientific articles can be evaluated by means of citations (Nieminen et al., 2006; Weale et al., 2004). In addition, citations of a research article is an important channel for disseminating its results (Nieminen et al., 2006). The USA is still leading in the absolute number of citations (see **Figure 4.8**). Unlike in the publications of water treatment processes and/or products related to nanotechnology, China is the second after the USA in citations instead of India with respect to nanomedicine. South Africa is still trailing behind the other nations in terms of citations. As stated already in **Subsection 5.4.1** (under citations of the publications in water treatment), according to Van Noorden (2017) "lack of citation cannot be interpreted as meaning that articles are valueless". For example, though South Africa's citations are lower, "tangible products are being developed in the country such as the discoveries of nanofibres at the University of the Free State which are meant to spur the growth of nerve cells and nanostructured gels for cell regeneration" (Chidanyika, 2016).

Collaborations amongst countries in the publications in medical fields: Discussion

Table 4.18 clearly shows that countries that have high absolute number of research articles through collaborations are leading in the total number of research articles. This is a strong confirmation that collaborations amongst nations has a significant influence on the publications of research articles thus leading to better scientific performance. For example, a number of authors have also found that research collaboration has a positive effect on publishing productivity (Groboljšek et al., 2014; Lee & Bozeman, 2005; Srivastava, 2012; Varnai et al., 2017). Unfortunately, **Table 4.18** also shows that South Africa has minimal collaborations with countries that have strong research outputs such as the USA (14 articles), China (0 articles) and India (13 articles). The low collaboration research outputs for South Africa with Brazil (0 article), Russia (0 article), India (14 articles) and China (14 articles) is quite surprising because in 2015 BRICS countries signed an MoU to establish a research and development collaborative programme amongst themselves (BRICS, 2015, 2019).

Disciplines and/or research areas in the publications in medical fields: Discussion

Both medicine and nanotechnology are diverse. **Figure 4.9** is a clear attestation of the diversity of the two fields – nanotechnology and medicine. In particular, nanotechnology being a general-purpose technology, typically, according to Pandza et al. (2011) demonstrates “its pervasiveness and inherent potential for opening new opportunities” in various disciplines. As the figure shows the prominent areas of applications of nanomedicine are in nanoscience, chemistry, materials science and pharmacology/pharmacy.

Patents in medical fields: Discussion

The mainspring of medical research, according to Framework (2013), is to “advance knowledge for the good of society; to improve the health of people worldwide; or to find better ways to treat and prevent diseases”. Moreover, “innovations in the health sciences have resulted in dramatic changes in the ability to treat diseases and improve the quality of life” (DiMasi et al., 2003). Unfortunately, it is a proven fact globally that the production of new drugs take longer than a decade in many cases from R&D itself to pre-clinical testing, clinical trials, and regulatory approval (Cockburn & Long, 2015).

This section discusses **Figure 4.10** and **Table 4.19** of **Chapter 4**. The patents in the figure and table were filed through WIPO by BRICS countries and the USA over a nine year period with respect to medical products and/or processes that contained nanomaterials. According to Cockburn and Long (2015) several studies, particularly in the USA, have found that patents are relatively more important to R&D in pharmaceuticals than in other industries. This may explain why the USA which is still leading in terms of patents filed has higher medical field patents than water treatment patents (compare **Figure 4.5** and **Figure 4.10**). In fact, all the BRICS countries (except South Africa) also have relatively higher patents in the medical field than in water treatment. According to **Figure 4.10**, China is in the second position followed by Russia, India and Brazil whereas South Africa has no patents filed through WIPO in the past 9 years. However, before 2010 South Africa (36 patents) filed more patents through WIPO than Brazil (26 patents) (see **Table 4.19**).

It must be noted also that despite all the patents, the opponents of patents in the medical field argue that "patents result in higher prices, making essential medicines less affordable" (Siddiqi, 2005). However, proponents of medical patents argue that "patent rights are essential to encourage innovation" (Siddiqi, 2005). Furthermore, Berner-Rodoreda et al. (2016) states that "high drug pricing is justified by the pharmaceutical industry to compensate for the cost of research and development (R&D) of new drugs. Without patents pharmaceutical R&D will come to a standstill, they argue".

Top 10 applicants for patents in medical fields: Discussion

Table 4.20 shows the top ten patent applicants for each of the BRICS nations and the USA. Unlike in the patents of nano-based water treatment processes and/or products the USA, Brazil and China all have patent applicants emanating only from firms and/or universities. Brazil also has more patents in the medical fields (i.e., 10) than in the water (only three) which confirms Cockburn and Long (2015)'s assertion that patents are relatively more important to R&D in pharmaceuticals than in other industries. South Africa (two), India (three) and Russia (two) all have individual patent applicants amongst the top 10 applicants. It is also noted from **Table 4.20** that apart from Brazil and South Africa, the rest of the other countries have patents applied through some universities in the USA. This may explain why South Africa and Brazil have low patenting capabilities; and there is no doubt that the USA has some of the best universities in the world dealing in nanotechnology research (StatNano, 2018).

5.5 Economic catch-up in nanotechnology-based processes and/or products in general: Discussion

As discussed in **Sections 2.8 and 4.4**, it is clear from **Table 4.21** that obtaining data that assesses economic impact of nano-enabled products and/or processes is difficult. For example, there is no readily available data for Brazil and South Africa. This is not surprising because although South Africa and Brazil have a modest number of research articles in nano-enabled products and/or processes, unfortunately, it is obvious that related patents (see **Figure 4.5** and **Figure 4.10**) are not growing at the same rate. This may explain why there is no information on the revenues of commercialised nano-based products and/or processes originating from South Africa and Brazil (see **Table 4.21**). UNESCO (2016) also noted that the contribution of the BRICS nations to nanotechnology except China, India and Russia is quite negligible.

In South Africa, though the government invests in late-stage R&D, intellectual property protection and the commercialization of novel technologies through TIA (UNESCO, 2010) and many other institutions (CSIR, 2017; DST, 2008; Mintek, 2019), the main constraint is the selection criteria. The selection criteria requires applicants to form a consortium and to propose a programme for diffusing their new technology to small, medium-sized and microenterprises (UNESCO, 2010). There is no doubt that the criteria is quite restrictive for individual inventors. Furthermore, Mufamadi (2016) states that “the development of nanotechnology in South Africa is hampered by many barriers such as regulation, standards, health & safety issues and public perception”.

As of 2013, Russia had over 500 companies that were actively manufacturing nanotech products providing more than US$15bn in sales, quarter of which was exported to other countries (UNESCO, 2016). This may be explained by the fact that, in recent past, nanotechnology has been embedded in the Russian policy agenda as the government seriously considers it as a key foundation in the process of modernisation and innovation (Westerlund, 2011).

5.6 Summary

This Chapter started by looking at the capability building strategies of South Africa for technological and economic catch-up, in general, and nanotechnology, in particular. It is clear from the results that South Africa has invested heavily in capability building strategies since the white paper on science and technology of 1996. For example, amongst a number of strategic initiatives, the country created the national research and development strategy which has a number of strategic functions. In terms of scientific publications the country's results are modest compared to the other BRICS countries. However, South Africa is performing poorly in terms of technological and economic catch-up in nano-enabled products and/or processes in general. In other words, South Africa has failed to use nanotechnology-related products and/or processes as a window of opportunity to catch-up with the developed nations despite significant investment by the government in nanotechnology.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Introduction

One contentious question that does not seem to have simple answers and thus has attracted researchers from various theoretical and conceptual backgrounds pertains to catch-up by some low-income countries with the developed countries, whilst other underdeveloped nations are not able to catch-up (Fagerberg & Verspagen, 2007). Various answers are given depending on the schools of thought by the scholars (Bentzen, 2011; Fagerberg & Verspagen, 2007; Gallup et al., 1999; Sachs et al., 2001). This research report addressed the issues of catch-up by South Africa through the following three questions:

(1) To what extent has South Africa created capacity for technological and economic catch-up, in general, and in nanotechnology, in particular?

(2) To what extent have water treatment and medical related nanotechnology based processes and/or products advanced technological catch-up by South Africa relative to its BRICS counterparts and the technologically advanced USA?

(3) What is the extent to which water treatment and medical related nanotechnology-based processes and/or products have advanced economic catch-up in South Africa relative to its BRICS counterparts and the technologically advanced USA?

The results of these questions were given in **Chapter 4** and discussed in **Chapter 5** through the following study objectives. The first objective was to determine the extent to which South Africa is creating capabilities, in general, for technological and economic catch-up with the developed world. Thereafter, the study evaluated capacity building strategies in the field of nanotechnology for technological and economic catch-up. Finally, and most importantly, the study interrogated whether nanotechnology is providing a ‘critical window’ for South Africa to catch-up technologically and economically with the developed world. Two fields in which nanotechnology is applied – water treatment and medicine – were the focus of the assessment for technological and economic catch-up.

From the aforementioned objectives of the study, this Chapter gives the conclusions that have been drawn from the findings in **Chapter 4** and the subsequent discussion in **Chapter 5**. The Chapter also makes recommendations and/or suggestions that may address some of the limitations found in the study and/or the catch-up narratives better in future.

6.1.2 General capability building strategies

It is evident from the study that South Africa has invested substantially on capability building institutions for technological and economic development, and as a result the country possesses a considerable number of competences in various fields. The country has a NIS that has just been reviewed (DST, 2018a). Indeed, the revised NIS is aimed at strengthening capacities and increasing the outputs which will allow South Africa to successfully compete scientifically, technologically and economically globally.

Following the specific functions of the NIS as stipulated by the OECD (1999), South Africa has successfully championed and/or achieved most of the functions. For example, the country has formulated policies that are aimed at increasing innovation, diffusion and transfer of technology (ASSAf, 2013). In addition, the country encourages entrepreneurship and in that regard, the government established the department of small business development (DSBD, 2019). Unfortunately, the country's R&D expenditure (% of GDP) has continued to diminish since 2010 (WorldBank, 2019). However, the country has a good enabling environment for research, and thus all its 26 publicly owned universities and publicly funded research institutions (e.g., Mintek, CSIR, HSRC, etc) are at the forefront of performing research. Without doubt, universities and publicly funded research institutions including private firms have contributed to the scientific, technological and economic performance of the country. Unfortunately, over the years universities and research institutions have continued to incur drastic reductions in government funding (as may be reflected in the diminishing R&D expenditure) thus reducing their research capabilities.

According to Henri and Wim (2000) "the quality of human resources is a prime factor in economic growth and competitiveness, and thus the investment in human capital explains to a large extent the present and the future of the skills and capabilities of countries". The OECD (2001) considers human capital as "the knowledge, skills, competencies and attributes embodied in individuals that facilitate the creation of personal, social and economic well-being". When looking at the number of pupils who either sit and/or even obtain a bachelor's pass from 2008-2017 (see **Table 4.4**), there is just a negligible increase. However, due to a number of interventions tailored to promote human resource development such as the introduction of the South African national research and development strategy, there has been a reasonable improvement in the number of scientists, engineers and technologists produced.

The study showed that there is a good industry-to-industry and public-to-private interactions. However, such interactions are not generating any and/or significant number of patents despite the interactions entailing that the parties are engaged in applied research. There is also reasonable personal mobility between interacting parties (industry-to-industry or public-to-private), and the government has also signed a number of MoUs with various countries. For example, one of the MoUs involves academic mobility of students, the university faculty and staff amongst the BRICS nations (BRICS, 2015). Indisputably, such movement of people and the knowledge they carry, to a certain degree, is important in the dissemination of innovation (Stevens, 1997).

6.1.3 Capability building strategies in nanotechnology

There is no doubt that nanotechnology is no longer a buzzword, but a reality (Perkel, 2016). The two terms 'nanoscience' or 'nanotechnology' are normally interchangeably used, but are simply science and engineering, respectively, carried out on the nanometre scale (Stupp, 2002). Various scholars acknowledge that nanotechnology has the potential to radically change a number of industries (Bhattacharya, 2015; Simate et al., 2013). This explains an enormous spending on nanotechnology R&D and start-ups by various governments, corporations, and venture capital investors (Flynn et al., 2013; Stupp, 2002).

Over the years, South Africa has also been in the league of developing capabilities in nanotechnology so as to tap into the technology's vast potential in a range of fields. As a result, in 2005, South Africa successfully launched the national nanotechnology strategy (DST, 2005) with a focus on areas likely to benefit the country such as water, energy, health care, chemical and bio-processing, mining and minerals, and advanced materials and manufacturing (DST, 2005; Saidi & Douglas, 2017).

Soon after the national nanotechnology strategy was established, a number of policies and strategies were also successfully developed namely, (1) public funding: the total spending in different aspects of nanotechnology R&D is reported to be over R170 million (DST, 2006; Musee et al., 2010); (2) national nanotechnology equipment programme: this programme provided ring-fenced grants to researchers through the NRF to purchase nanotechnology-related research equipment (Makhoba & Pouris, 2017; NRF, 2015). Though this strategy came to an end in 2015, it has benefited a number of universities and research institutes (e.g., Mintek and CSIR) that are vigorously engaged in nanotechnology; (4) nanotechnology innovation centres: the two centres at Mintek and CSIR have the responsibility to commercialise nanotechnology-enabled products that are directed at seeking solutions that address challenges facing South African societies (CSIR, 2017). The two centres have successfully achieved their mandate in a number of areas (CSIR, 2017; Mintek, 2018); (5) human capital development: the importance of human capital in innovation and/or economic development has been factored by a lot of scholars in their models (Aleknavičiūtė et al., 2016; Lucas Jr, 1988; Mariz-Pérez et al., 2012). In view of the importance of skills required in nanotechnology, South Africa has instituted a master's degree programme in nanoscience at four universities (Dube & Ebrahim, 2017; Khoza, 2018) and initiated research chairs programme (DST, 2008) whose focus is research activities that advance scientific performance in nanotechnology in South Africa and also subsequently contribute to the training of scientists and postgraduates (Khoza, 2018). The programmes of human capital development have been quite successful based on the number of students who graduated through the master's programme (Khoza, 2018) and the number of research chairs on nanotechnology (see **Table 4.13**); (6) DST-NRF centre of excellence in strong materials: The CoE has advanced scientific knowledge through publications, technological knowhow through patents and has contributed to human capital development by training postgraduate students (masters and PhDs).

In summary, in view of various strategies by South Africa, it is clear that the country is striving to become a nanotechnology hub. However, the patenting results (see **Figure 4.5** and **Figure 4.10)** and economic impact results **(**see **Table 4.21)** are somewhat disappointing.

6.1.4 Scientific and Technological catch-up

The generation of scientific knowledge and its application in the development of technology, economic and societal necessities is more vital today than ever before. This study used publications as indicators for scientific performance and patents as indicators for technological performance. In fact, Huang et al. (2011) considers publications and patents as excellent representations of the outcomes of scientific and technological efforts, respectively.

It is clear from the results in **Chapter 4** and the subsequent discussion in **Chapter 5** that the USA has the highest total number of scientific publication in both nanotechnology-enabled water treatment and medicine from 2010-2018. However, the year-by-year data for water treatment showed that China surpassed the USA in terms of scientific publications in 2016; and China is also likely to surpass the USA in nanomedicine publications within a year or so. The recent high number of scientific publications by China is not surprising because in general, according to Veugelers (2017) "Chinese R&D investment in science and technology has grown remarkably, with the rate of growth greatly exceeding those of the USA and the European Union". Moreover, China also has a number of scientific research institutes that are seriously engaged in large-scale research (Wu & Fan, 2010). Another BRICS country that was doing quite well in scientific publications of nanotechnology-enabled water treatment is India, but dropped significantly since 2016. The rest of the BRICS nations including South Africa are not performing well in the two fields in both a 9-year period and on a year-by-year basis.

The USA is leading by far in the two fields in both citations of the scientific articles and patents filed through WIPO. However, based on China's patent applications and approvals in other fields (Long & Wang, 2019) it is more likely that, in the near future, it will surpass the USA in nanotechnology-enabled water treatment and medicine. In fact, in general, it surpassed the USA and Japan in 2011 to become the largest patent applicant country (Long & Wang, 2019). The growth in patent applications and approvals by China is due to the adoption of the PPPs (Long & Wang, 2019). Nevertheless, the quality of Chinese patents has also declined due to the PPPs according to Long and Wang (2019).

The results of the study showed that there are more patents in medical fields than in nano-based water treatment, which confirms the argument by some scholars like Cockburn and Long (2015) that patents are relatively more important to R&D in pharmaceuticals than in other industries. The study also shows that firms and/or universities are the dominant patent applicants in the USA and Brazil whereas Russia, India and South Africa also have individual patent applicants in all fields. China has individual patent applicants only in nano-based water treatment.

Collaborations are acknowledged as quite significant in scientific and technological activities globally. Though the BRICS have a number of MoUs related to science, technology and innovation there is very little collaboration that lead to scientific publications. The USA, China and India collaborate quite strongly in nanomedicine than in nanotechnology-enabled water treatment processes and/or products. This may be explained from the fact that some researchers have found that patents are relatively more important to R&D in pharmaceuticals than in other industries (Cockburn & Long, 2015).

The diversity of nanotechnology is displayed in the various disciplines it is applied in the two fields in this study (see **Figure 4.4** and **Figure 4.9**). Indeed, the diversity and complexity of nanotechnology is recognised by many scholars in view of the types of materials available and being developed, as well as the seemingly limitless potential uses of the materials (EPA, 2007). Niosi and Reid (2007) describe nanotechnology as an enabling technology that provides tools, materials and devices for further technological development.

6.1.5 Economic catch-up

As extensively shown in **Section 6.1.3** the government of South is quite keen to advance nanotechnology and thus, the country has invested a substantial amount of funds into nanotechnology related research in various areas. The study has clearly shown that though the scientific performance (research publications) of the nation in the past 9 years is below that of other BRICS nations except Russia, the country has been in an upward trajectory since 2016 in nano-enabled products for water. The study also shows that South Africa is catching up scientifically with Brazil in nano-enabled products for water.

This study opted to evaluate the economic impact based on the entire nanotechnology-enabled products and/or processes for the revenue data instead of water and medicine only. This was because of the difficulty in obtaining the required data (Baucher et al., 2013) and disagreements in the definitions of nanomaterials (Baucher et al., 2013; Ouellette, 2015a, 2015b). Health and safety implications of nanomaterials in water and medical field applications may also restrict the commercialisation of products and/or processes in the fields (Perkel, 2016; Yah et al., 2012). As a result, the economic contribution of nano-based products and processes in South Africa and Brazil is almost non-existence as indicated in **Table 4.21**.

Ideally, South Africa is not using nanotechnology as a 'window of opportunity' to catch-up with the technologically developed nations. As already discussed in **Section 4.4** and **5.5,** Mufamadi (2016) summed it up and states that "the development of nanotechnology in South Africa is hampered by many barriers such as regulation, standards, health & safety issues and public perception". On the other hand the contribution of the USA, China and Russia to nanotechnology-enabled products and or/ processes is quite significant (see **Table 4.21**).

6.2 Recommendations

Though this study has generated valuable amount of results, there were also some limitations encountered. Therefore, with the knowledge that has been gathered from this work, the following recommendations and/or further studies are proposed**.**

6.2.1 Patent incentives

The government is investing handsomely in nanotechnology related capability building strategies, and the country's scientific performance is modest. However, the country seem to be failing to convert scientific inventions into innovations through the generation of patents and licenses of research outputs. One of the hindrances often cited by scholars for insufficient patenting by many firms is due to the cost involved in the whole patenting process from a filing fee to patent protection and maintenance fees. It is recommended that incentives aimed at minimising the cost and administrative support be provided, particularly to individual inventors.

6.2.2 Commercialisation of research

According to Bezuidenhout (2018) “commercialisation of intellectual property, also known as technology transfer, is the process of transferring scientific research findings from university or firm or an individual to market” for the purpose of obtaining economic or social value from the invention. The results of this study shows that South Africa is failing to commercialise its patented inventions despite having institutions such as TIA, CSIR, innovation hubs, etc., that are mandated to do so and/or are in the forefront of assisting the commercialisation of inventions. There are a number of barriers to commercialisation, but this study will only cite one, i.e., technology push. Previous and/or existing patents are not being commercialised because the market for the technology may not have been taken into consideration at the initial stage of technology development. Therefore, it is important that technology developers in South Africa assess the market needs at industry and/or community level. Ideally, there is need for strong partnerships, interaction and collaboration between industry and inventors of technology.

6.2.3 Relaxation of technology innovation agency criteria for funding commercialisation

As previously discussed (see **Table 4.2**), TIA promotes technology development from proof of concept to the commercialisation of research outputs. Among the selection criteria, according to UNESCO (2010), is that “applicants are expected to form a consortium and to propose a programme for diffusing their new technology to small, medium-sized and microenterprises”. The criteria, as it stands, is not feasible for individual inventors to enter into a consortium with others who may not have related inventions. This study recommends that individual inventors be allowed to tender as individuals for the following TIA funds: the Seed Fund, the Technology Development Fund and the Commercialisation Support Fund. This recommendation should be allowed as long as there is market available for the invention.

6.2.4 Comparison of capability building strategies of BRICS based on the national innovation systems

This study used the functions of the NIS together with the mechanism of knowledge flow within the NIS as the capability building blocks for innovation in South Africa. Future studies should consider comparing the NIS of each BRICS nations based on the functions of the NIS and mechanisms of the dissemination of knowledge as given by the OECD (1999) and OECD (1997). This may give an insight into the differences seen in this study pertaining to the scientific, technological and economic performance of each BRICS nation.

6.2.5 Applied research

A review of **Table 4.10** and the discussion thereafter (**Subsection 5.2.6**) shows that the main outputs of academic/private interactions is academic publications (or dissertations or thesis), and graduates. HESA (2012) also reported that in academic/private collaborations new or improved products and processes were not common which implies that there is less focus on technological performance in the collaborations. It is recommended that academic/private collaborations should focus on applied research that bring technological performance which would improve the country‘s technological catch-up with the forerunners. In fact Lee (2016) suggests that “the key to economic catch-up lies in specific technological strategies”. For example, the importance of the concept of technological catch-up is that many countries including Korea and Taiwan moved away from the middle class status to the high income group of economies, to a large extent, due to technological catch-up (Yusuf, 2012).

6.2.6 Survey of unpatented innovation and nanotechnology start-ups

A number of reasons have been mentioned by various scholars that hinder the patenting of innovations (Archibugi, 1992; Arundel, 2001; Fontana et al., 2013). Some of the reasons include the high cost involved in the whole patenting process, industrial secrecy, and patents not being technically patentable. Future studies should consider carrying out a survey to establish the number and nature of innovations that have not been patented in South Africa. It is also important to establish, in future studies, the number and nature of nanotechnology start-ups in South Africa since the nanotechnology strategy was established

6.2.7 Mixed methods approach

The definitions of both qualitative and quantitative methods were outlined in Chapter 3. Though this study was based on a quantitative approach, it is important to appreciate the relevance of qualitative analysis in this study. This study recommends that future studies should include mixed methods approach. Many researchers agree that by mixing both quantitative and qualitative research and data, the researcher gains the breadth and an in depth understanding and corroboration, while offsetting the weaknesses inherent to using each approach by itself (FoodRisC, 2016). Ideally, the inclusion of qualitative methods could have helped in validating or corroborating the results obtained from the quantitative method. Furthermore, such a method may give an opportunity to researchers to interview some of the companies that are involved in nanotechnology-enabled water treatment and medical applications.

REFERENCES

ACAPS (2013). Qualitative and quantitativecresearch techniques for humanitarian needs assessment: An introductory brief. Retrieved from http://www.orange.ngo/wp-content/uploads/2017/06/Qualitative-and-Quantitative-Research-Techniques.pdf

Accenture/Bankinter, & (2006). Nanotechnology: The industrial revolution of the 21st century. Retrieved from https://www.fundacionbankinter.org/documents/20183/137602/Publicacion+PDF+IN+FTF_Nanotecnologia.pdf/ca7d4f6e-e2c9-49d4-b6ee-c2200d2926b0

Adak, M. (2015). Technological progress, innovation and economic growth; the case of Turkey. *Procedia-Social and Behavioral Sciences, 195*, 776-782.

AfricaCheck. (2019). Factsheet: Funding and the changing face of South Africa's public universities. Retrieved from https://africacheck.org/factsheets/factsheet-funding-changing-face-sas-public-universities/

Ahmadvand, E., Salami, S. R., Soofi, J. B., & Tabatabaeian, S. H. (2018). Catch-up process in nanotechnology start-ups: The case of an Iranian electrospinning firm. *Technology in Society, 55*, 1-8.

Akamatsu, K. (1962). A historical pattern of economic growth in developing countries. *The developing economies, 1*(1), 3-25.

Akpolat, H., & Chang, L. (2008). A comparative analysis of the national innovation systems of China and Australia. *Asian Journal on Quality, 9*(1), 153-167.

Aksnes, D. W., Langfeldt, L., & Wouters, P. (2019). Citations, citation indicators, and research quality: An overview of basic concepts and theories. *SAGE Open, 9*(1), 1–17.

Aleknavičiūtė, R., Skvarciany, V., & Survilaitė, S. (2016). The role of human capital for national innovation capability in EU Countries. *Economics and Culture, 13*(1), 114-125.

Alencar, M., Porter, A., & Antunes, A. (2007). Nanopatenting patterns in relation to product life cycle. *Technological Forecasting & Social Change, 74*, 1661-1680.

Alexander, L. K., Lopes, B., Ricchetti-Masterson, K., & Yeatts, K. B. (2015). Cross-sectional studies. . Retrieved from https://sph.unc.edu/files/2015/07/nciph_ERIC8.pdf

Alkhaldi, F. M. K. (2003). *An integration of information technology, culture of knowledge transfer and innovative work environment in support of organisationsal knowledge creation activities.* (PhD). University of Huddersfield, Retrieved from http://eprints.hud.ac.uk/id/eprint/4617/1/DX224534.pdf

Alonso, J. A., Cortez, A. L., & Klasen, S. (2014). LDC and other country groupings: How useful are current approaches to classify countries in a more heterogeneous developing world? Retrieved from http://www.un.org/en/development/desa/policy/cdp/cdp_background_papers/bp2014_21.pdf

Altaher, A. M. (2010). Knowledge management process implementation 2011. *International Journal of Digital Society, 1*(4), 265-270.

Amabile, T. M. (1988). A model of creativity and innovation in organizations. *Research in organizational behavior, 10*(1), 123-167.

Amsden, A. H. (1994). Why isn't the whole world experimenting with the East Asian model to develop?: Review of the East Asian miracle. *World Development, 22*(4), 627-633.

Anbumozhi, V., & Yao, X. (2017). *Remaking energy policies for global sustainability: The case of flying geese model and path dependencies in East Asia*. Retrieved from http://www.eria.org/ERIA-DP-2017-08.pdf

Andrew, D. P., & Pedersen, P. M. (2011). *Research methods and design in sport management*. Champaign, United States: Human Kinetics.

Antonelli, C. (1999). Localised technological change and the evolution of standards as economic institutions. In A. D. Chandler, P. Hagström, & Ö. Sölvell (Eds.), *The dynamic firm: the role of technology, strategy, organization and regions*. Oxford: Oxfor University Press.

Appiah-Kubi, K. (2015). Policy making process. Retrieved from file:///C:/Users/a0009328/Downloads/DRUSSA%20ISSER%20Training_Policy%20Influence_APPIAH-KUBI,%2016%20Dec%202015.pdf

Archibugi, D. (1992). Patenting as an indicator of technological innovation: a review. *Science and Public Policy, 19*(6), 357-368.

Archibugi, D., & Planta, M. (1996). Measuring technological change through patents and innovation surveys. *Technovation, 16*(9), 451-519.

Arundel, A. (2001). The relative effectiveness of patents and secrecy for appropriation. *Research Policy, 30*(4), 611-624.

Ashley, P., & Boyd, B. W. (2006). Quantitative and qualitative approaches to research in environmental management. *Australasian Journal of environmental management, 13*(2), 70-78.

ASSAf. (2013). Review of the state of science, technology and innovation (STI) system in South Africa. Retrieved from http://research.assaf.org.za/bitstream/handle/20.500.11911/79/2013_assaf_sti_system_sa.pdf?sequence=1&isAllowed=y

Atta-Mensah, J. (2015). The role of science, technology, and innovation in Africa's growth Retrieved from https://africaupclose.wilsoncenter.org/the-role-of-science-technology-and-innovation-in-africas-growth-1/

Ayankoya, K. (2016). Entrepreneurship in South Africa - Solution. Retrieved from https://www.academia.edu/3878378/ENTREPRENEURSHIP_IN_SOUTH_AFRICA

Aylward, S. (2019). Call for closer collaboration between macadamia industry and government. Retrieved from https://southcoastherald.co.za/342980/call-closer-collaboration-macadamia-industry-government/

Baković, T. (2010). Managing innovation systems in transition economies. *EFZG working paper series*(01), 1-11.

Baradello, C. S., & Salazzaro, A. (2012). The role of imitation in global high-tech product development. *Symphonya: Emerging Issues in Management*(1), 57-71.

Barkley, A., & Barkley, P. W. (2013). *Principles of agricultural economics*. London: Routledge.

Bates, D. L., & Eldredge, D. L. (1980). *Strategy and policy: Analysis, formulation, and implementation*. Dubuque, Iowa: WCB/McGraw-Hill.

Batinge, B., Musango, J. K., & Brent, A. C. (2017). Leapfrogging to renewable energy: The opportunity for unmet electricity markets. *South African Journal of Industrial Engineering, 28*(4), 32-49.

Baucher, M.-A., Scott, R., Cannizzaro, C., Standridge, S., Nesbitt, E., & Fadel, T. (2013). *Symposium on assessing the economic impact of nanotechnology: Synthesis report*. Retrieved from Washington DC: http://eprints.internano.org/1918/1/Washington%20Symposium%20Report_final.pdf

Bawa, A., Alper, H., Cozzens, S., Krishna, V., & Woods, D. R. (2013). Review of the DST-NRF centres of excellence programme. Retrieved from https://www.nrf.ac.za/sites/default/files/documents/Final%20NRF%20CoE%20Report.pdf

Bayarcelik, E. B., & Taşel, F. (2012). Research and development: Source of economic growth. *Procedia-Social and Behavioral Sciences, 58*, 744-753.

Beck, V., Evans, R., Behrendt, F., Raj, B., Oh, M., Lloyd, P. J., Loughhead, J., & Savitz, M. (2013). *Opportunities for low-carbon energy technologies for electricity generation to 2050* (1921388242). Retrieved from Virginia: http://digitalknowledge.cput.ac.za/bitstream/11189/2467/4/Opportunities%20for%20Low-Carbon%20Energy.pdf

Bentzen, J. S. (2011). *Why are some countries richer than others? Cross-country and cross-regional empirical studies.* (PhD). University of Copenhagen, University of Copenhagen, Denmark. Retrieved from https://www.econ.ku.dk/forskning-og-publikationer/Publikationer/ph.d_serie_2007-/Ph.D.151.pdf

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

Berner-Rodoreda, A., Lukow, M., & Steinwachs, L. (2016). *Medicines patents, access and innovation: Analysis*. Retrieved from Berlin: https://www.medbox.org/medicines-patents-access-and-innovation/download.pdf

Bezuidenhout, F. R. (2018). *Mini-dissertation submitted in partial fulfilment of the requirements for the degree Master of Business Administration at the North-West University.* (Master of Business Administration). Notrh West University, Retrieved from https://repository.nwu.ac.za/bitstream/handle/10394/30624/Bezuidenhout_FR_2018.pdf?sequence=1&isAllowed=y

Bhattacharya, S. (2015). Nanotechnology and Development: What's in it for Emerging Countries? *Journal of Scientometric Research, 4*(3), 210-210.

Bhattacharya, S., & Bhati, M. (2011). China's emergence as a global nanotech player: Lessons for countries in transition. *China Report, 47*(4), 243-262.

Bhattacharya, S., Jayanthi, A., & Shilpa, S. (2012). Nanotechnology Development in India: Investigating ten years of India's efforts in capacity building. Retrieved from https://www.researchgate.net/publication/301637179_Nanotechnology_Development_in_India_Investigating_Ten_Years_of_India's_Efforts_in_Capacity_Building

Bhattacharya, S., Pushkaran, J. A., & Shilpa, S. (2012). Nanotechnology research and innovation in India: Drawing insights from bibliometric and innovation indicators. Retrieved from https://www.researchgate.net/publication/301637258_Nanotechnology_Research_and_Innovation_in_India_Drawing_Insights_from_Bibliometric_and_Innovation_Indicators

Bhattacharya, S., & Shilpa, S. (2011). Mapping nanotechnology research and innovation in India. *Journal of Library & Information Technology, 31*(5), 349-358.

Bizcommunity. (2018). Automation industry calls for collaboration to make SA globally competitive. Retrieved from https://www.bizcommunity.com/PDF/PDF.aspx?l=196&c=94&ct=1&ci=173760

Bornmann, L., Mutz, R., Neuhaus, C., & Daniel, H.-D. (2008). Citation counts for research evaluation: standards of good practice for analyzing bibliometric data and presenting and interpreting results. *Ethics in science and environmental politics, 8*(1), 93-102.

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

Boslaugh, S. (2007). *Secondary data sources for public health: A practical guide*. Cambridge: Cambridge University Press.

Bozkurt, C. (2015). R&D expenditures and economic growth relationship in Turkey. *International Journal of Economics and Financial Issues, 5*(1), 188-198.

Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies 'Engines of growth'? *Journal of econometrics, 65*(1), 83-108.

BRICS. (2015). Memorandum of understanding on establishment of the BRICS network university. Retrieved from https://nu-brics.ru/media/uploads/filestorage/documents/MoU_SU_BRICS.pdf

BRICS. (2019). BRICS multilateral joint science and technology research collaboration: 2019 Call for joint project proposals. Retrieved from https://www.nrf.ac.za/sites/default/files/3rdBRICS%20Multilateral%20Call_SA%20Guideline.pdf

Brown, A. J. (2013). *Introduction to the world economy*: Routledge.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., Hauff, V., Lang, I., Shijun, M., & de Botero, M. M. (1987). Our common future (\'brundtland report\').

Bubou, G. M., Siyanbola, W. O., Ekperiware, M. C., & Gumus, S. (2014). Science and technology entrepreneurship for economic development in Africa (SEEDA). *International Journal of Scientific and Engineering Research, 5*(3), 921-927.

Cain, C. T. (2003). *Building down barriers: a guide to construction best practice*. London: Routledge.

Canadian Institute for Knowledge Development (CIKD). (2020). Scopus vs ISI web of science; Which One?. Retrieved from https://ieconferences.com/scopus-vs-isi-wos-which-one/

Cancino, C. A., La Paz, A. I., Ramaprasad, A., & Syn, T. (2018). Technological innovation for sustainable growth: An ontological perspective. *Journal of Cleaner Production, 179*, 31-41.

Capek, I. (2006). Science and nanotechnology - Fundamental principles and colloidal particles. *Nanocomposite Structures and Dispersions, 23*, 1-301.

Cappy, A., Stievenard, D., & Vuillaume, D. (2002). Nanotechnology: The next industrial revolution? Retrieved from http://amsacta.unibo.it/160/1/GaAs_PL1_Cappy.pdf

Carayannis, E. G., & Provance, M. (2008). Measuring firm innovativeness: towards a composite innovation index built on firm innovative posture, propensity and performance attributes. *International Journal of Innovation and Regional Development, 1*(1), 90-107.

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of evolutionary economics, 1*(2), 93-118.

Carpenter, C. R., Cone, D. C., & Sarli, C. C. (2014). Using publication metrics to highlight academic productivity and research impact. *Academic emergency medicine, 21*(10), 1160-1172.

Cerqueti, R., Quaranta, A. G., & Ventura, M. (2016). Innovation, imitation and policy inaction. *Technological Forecasting and Social Change, 111*, 22-30.

Chen, D., & Li-Hua, R. (2011). Modes of technological leapfrogging: Five case studies from China. *Journal of Engineering and Technology Management, 28*(1-2), 93-108.

Chidanyika, T. (2016). Nanomedicine in SA: the future and the concerns. Retrieved from https://www.npep.co.za/newsletter/issues/october-2016/nanomedicine-in-sa-the-future-and-the-concerns/

Chobotová, M., & Rylková, Ž. (2014). Measurement of innovation performance. *International Journal of Economics and Management Engineering, 8*(7), 2085-2090.

Choudhury, P. (2017). Innovation outcomes in a distributed organization: Intrafirm mobility and access to resources. *Organization science, 28*(2), 339-354.

Clark, P. V. L., Anderson, N., Wertz, J. A., Zhou, Y., Schumacher, K., & Miaskowski, C. (2015). Conceptualizing longitudinal mixed methods designs: A methodological review of health sciences research. *Journal of mixed methods research, 9*(4), 297-319.

Cloete, E., Buckley, C., Godfrey, L., Hildebrandt, D., Makhafola, M., Pouris, A., van Zyl, E., & Watson, J. (2014). The state of green technologies in South Africa. Retrieved from http://sro.sussex.ac.uk/id/eprint/53002/1/8-Jan-2015-WEB-526305-ASSAF-Green-Tech-mail.pdf

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

Coccia, M. (2018). Socioeconomic driving forces of scientific research. *arXiv preprint arXiv:1806.05028*.

Cockburn, I., & Long, G. (2015). The importance of patents to innovation: updated cross-industry comparisons with biopharmaceuticals. *Expert Opinion on Therapeutic Patents, 25*(7), 739-742.

Collins, T. (2015). Imitation: A catalyst for innovation and endogenous growth. *Economic Modelling, 51*, 299-307.

Colombatto, E. (2006). On economic growth and development. *The Review of Austrian Economics, 19*(4), 243-260.

Connolly, M. (2003). The dual nature of trade: measuring its impact on imitation and growth. *Journal of Development Economics, 72*(1), 31-55.

Connolly, M., & Valderrama, D. (2005). *VNorth&South technological diffu& sion and dynamic gains from trade*. Retrieved from

Conte, A., & Vivarelli, M. (2014). Succeeding in innovation: key insights on the role of R&D and technological acquisition drawn from company data. *Empirical Economics, 47*(4), 1317-1340.

Cornish, L. (2019). DST-NRF centre of excellence in strong materials. Retrieved from https://www.wits.ac.za/strongmaterials/

Cozzens, S., Cortes, R., Soumonni, O., & Woodson, T. (2013). Nanotechnology and the millennium development goals: water, energy, and agri-food. *Journal of Nanoparticle Research, 15*(11), 2001.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. London: Sage publications.
CSIR. (2015). SA positions itself to attract research investors. Retrieved from https://www.enca.com/south-africa/sa-positions-itself-attract-research-investors
CSIR. (2017). CSIR nano-centre celebrates 10 years of ground-breaking research. Retrieved from https://www.csir.co.za/csir-nano-centre-celebrates-10-years-ground-breaking-research
CSTP. (2001). The 2nd science and technology basic plan (2001-2005). Retrieved from https://www8.cao.go.jp/cstp/english/basic/2nd-BasicPlan_01-05.html
Currie, D., Levine, P., Pearlman, J., & Chui, M. (1999). Phases of imitation and innovation in a North-South endogenous growth model. *Oxford Economic Papers, 51*(1), 60-88.
Dainty, A. R., Millett, S. J., & Briscoe, G. H. (2001). New perspectives on construction supply chain integration. *Supply chain management: An international journal, 6*(4), 163-173.
de Almeida, L., Fatima, M., & Caldas de Moraes, C. A. (2013). Diffusion of Emerging Technologies for Sustainable Development: Prospective Assessment for Public Policies. *Journal of technology management & innovation, 8*, 20-20.
de Almeida, M. F. L., de Moraes, C. A. C., & de Melo, M. A. C. (2015). Technology foresight on emerging technologies: implications for a national innovation initiative in Brazil. *Journal of technology management & innovation, 10*(2), 183-197.
de Groenendaal, H. v. (2018). Nanotechnology: An industry taking off in SA. Retrieved from https://www.ee.co.za/article/nanotechnology-a-new-industry-taking-off.html
Dejardin, M. (2000). Entrepreneurship and economic growth: an obvious conjunction? An introductive survey to specific topics. Retrieved from https://econwpa.ub.uni-muenchen.de/econ-wp/dev/papers/0110/0110010.pdf
Deloitte. (2012). Deloitte press release: Collaboration is key to improving South Africa competitiveness. Retrieved from http://pressoffice.mg.co.za/deloitte/PressRelease.php?StoryID=232200
DePoy, E., & Gitlin, L.N. (2016). Introduction to research:understanding and applying multiple strategies. St. Louis, Missouri: Elsevier Inc.
Desai, N. (2013). Nanotechnology. Retrieved from http://www.nishithdesai.com/information/areas-of-service/industry/nanotechnology.html
DHET. (2009). Human resource development strategy for South Africa (HRD-SA) 2010 – 2030. Retrieved from https://www.agriseta.co.za/downloads/HRDS_SA.pdf
DHET. (2015). Research outputs policy. Retrieved from http://www.dhet.gov.za/Policy%20and%20Development%20Support/Research%20Outputs%20policy%20gazette%202015.pdf
DHET. (2016). Report on the evaluation of the 2014 universities's research output. Retrieved from http://www.dhet.gov.za/Policy%20and%20Development%20Support/Report%20on%20the%20outcomes%20of%20the%202014%20universities%20research%20outputs.pdf
DHET. (2017). Report on the evaluation of the 2015 universities's research output

Retrieved from http://www.dhet.gov.za/Policy%20and%20Development%20Support/Report-2015-Research-Outputs-final-version.pdf
DHET. (2018). Report on the evaluation of the 2016 universities's research output

Retrieved from http://www.dhet.gov.za/Policy%20and%20Development%20Support/REPORT%20ON%20THE%20EVALUATION%20OF%20THE%202016%20UNIVERSITIES%20RESEARCH%20OUTPUT.pdf
DHET. (2019a). Annual performance plan 2019/2020. Retrieved from http://www.dhet.gov.za/SiteAssets/Media%20Release%20and%20Statements%202019/DHET%202019_20%20Annual%20Performance%20Plan.pdf
DHET. (2019b). Report on the evaluation of the 2017 universities's research output. Retrieved from http://www.dhet.gov.za/SiteAssets/REPORT%20ON%20THE%20EVALUATION%20OF%20THE%202017%20UNIVERSITIES%20RESEARCH%20OUTPUT%20April.pdf
DiMasi, J. A., Hansen, R. W., & Grabowski, H. G. (2003). The price of innovation: new estimates of drug development costs. *Journal of health economics, 22*(2), 151-185.
DoE. (2008). Classification of educational subject matter: August 2008. Retrieved from https://www.che.ac.za/sites/default/files/publications/CESM_August2008.pdf
DSBD. (2019). Department of small business development (DSBD). Retrieved from https://nationalgovernment.co.za/units/view/37/department-of-small-business-development-dsbd
DST. (2005). The natiional nanotechnology strategy. Retrieved from https://www.sun.ac.za/english/research-innovation/Research-Development/Documents/Biosafety/ENGLISH/National_Nanotechnology_Strategy.pdf
DST. (2006). DST annual report 2005/2006. Retrieved from https://www.gov.za/sites/default/files/gcis_document/201409/dstannualreport0506s.pdf
DST. (2008). Nanoscience and nanotechnology : 10-year research plan. Retrieved from https://www.gov.za/sites/default/files/gcis_document/201409/nanotechnology-researchplanfinalsmallreduce.pdf
DST. (2010). Ten-year innovation plan. Retrieved from https://www.sagreenfund.org.za/wordpress/wp-content/uploads/2015/04/10-Year-Innovation-Plan.pdf
DST. (2012). Final report of the ministerial review committee on science, technology and innovation landscape in South Africa. Retrieved from http://thornton.co.za/resources/35392_gen425.pdf
DST. (2015). Government funding for scientific and technological activities. Retrieved from https://www.dst.gov.za/images/2017/2015-16-Report-on-Government-Funding-for-STAs01.pdf
DST. (2018a). Daft white paper on science, technology and innovation Retrieved from https://www.dst.gov.za/images/2018/white-pate-on-STI-7_09-FINAL.pdf
DST. (2018b). Official guide to South Africa 2017/18: Science and Technology. Retrieved from

https://www.gcis.gov.za/sites/default/files/docs/resourcecentre/pocketguide/20-Science%20and%20Technology-1718.pdf
DTI. (2015). Full report implementation and impact evaluation of the technology and human resources for industry programme (THRIP). Retrieved from https://evaluations.dpme.gov.za/evaluations/502/documents/9c3b49c2-121a-48cd-9e99-a54eff9771fb
Dube, A., & Ebrahim, N. (2017). The nanomedicine landscape of South Africa. *Nanotechnology Reviews, 6*(4), 339-344.
Dulaimi, M., Akintoye, A., & Main, J. (2007). Collaborative relationships in construction: the UK contractors' perception. *Engineering, construction and architectural management, 14* (6), 597-617.
Dutta, S., & Weiss, A. M. (1997). The relationship between a firm's level of technological innovativeness and its pattern of partnership agreements. *Management science, 43*(3), 343-356.
Ebner, A. (2004a). Development strategies and innovation policies in globalisation: The case of Singapore. In S. Mani & H. Romijn (Eds.), *Innovation, learning and technological dynamism of developing countries* (pp. 48-76). Tokyo: United Nations University Press.
Ebner, A. (2004b). Innovation policies and locational competitiveness: Lessons from Singapore. *Asian Journal of Technology Innovation, 12*(2), 47-66.
EBRD. (2014). Innovation in transition. Retrieved from file:///C:/Users/a0009328/Downloads/tr14.pdf
Edler, J., Cunningham, P., Gök, A., & Shapira, P. (2013). Impacts of innovation policy: Synthesis and conclusions. Retrieved from http://www.innovation-policy.org.uk/share/20_Impacts%20of%20Innovation%20Policy%20Synthesis%20and%20Conclusion_linked.pdf
Edler, J., & Fagerberg, J. (2017). Innovation policy: What, why, and how. *Oxford Review of Economic Policy, 33*(1), 2-23.
Edquist, C. (2004). Reflections on the systems of innovation approach. *Science and Public Policy, 31*(6), 485-489.
Edquist, C. (2010). Systems of innovation perspectives and challenges. *African Journal of Science, Technology, Innovation and Development, 2*(3), 14-45.
Elhanan, H. (1998). *General purpose technologies andveconomic growth*. Cambridge, Massachusetts The MIT Press.
Emuze, F., & Smallwood, J. J. (2014). Collaborative working in South African construction: contractors' perspectives. *Journal of Engineering, Design and Technology, 12*(3), 294-306.
Enkel, E., & Gassmann, O. (2010). Creative imitation: exploring the case of cross-industry innovation. *R&d Management, 40*(3), 256-270.
EPA. (2007). Nanotechnology white paper Retrieved from https://www.epa.gov/sites/production/files/2015-01/documents/nanotechnology_whitepaper.pdf
EPO. (2013). Nanotechnology and patents. Retrieved from http://documents.epo.org/projects/babylon/eponet.nsf/0/623ECBB1A0FC13E1C12575AD0035EFE6/$File/nanotech_brochure_en.pdf
Eriksson, S. (2005). Innovation policies in South Korea and Taiwan. Retrieved from https://pdfs.semanticscholar.org/4ea3/b34a624507e60b0f9a388c057a9f90ff682e.pdf

Ezema, I., Ogbobe, P., & Omah, A. (2014). Initiatives and strategies for development of nanotechnology in nations: a lesson for Africa and other least developed countries. *Nanoscale research letters, 9*(1), 133-133.
Ezema, I. C., Ogbobe, P. O., & Omah, A. D. (2014). Initiatives and strategies for development of nanotechnology in nations: a lesson for Africa and other least developed countries. *Nanoscale research letters, 9*(1), 133.
Fabricant, S. (1954). Economic progress and economic change. In S. Fabricant (Ed.), *Economic Progress and Economic Change*. New York: NBER.
Fagerberg, J., & Godinho, M. M. (2004). Innovation and catching-up. In J. Fagerberg, D. Mowery, & R. Nelson (Eds.), *The Oxford Handbook of Innovation*. Oxford: Oxford University Press.

Fagerberg, J., & Srholec, M. (2008). National innovation systems, capabilities and economic development. *Research Policy, 37*(9), 1417-1435.
Fagerberg, J., & Verspagen, B. (2007). Innovation, growth and economic development: Have the conditions for catch-up changed? *International Journal of Technological Learning, Innovation and Development, 1*(1), 13-33.
Fairbrother, G. P. (2014). Quantitative and qualitative approaches to comparative education. In B. Mark, A. Robert Bob, & M. Mark (Eds.), *Comparative Education Research*. Switzerland: Springer.
Fankhauser, M., Moser, C., & Nyfeler, T. (2018). Patents as early indicators of technology and investment trends: analyzing the microbiome space as a case study. *Frontiers in bioengineering and biotechnology, 6*(84), 1-7.
Fantom, N., Fu, H., & Prince, W. C. (2014). LICs, LMICs, UMICs, and HICs: classifying economies for analytical purposes. Retrieved from http://blogs.worldbank.org/opendata/lics-lmics-umics-and-hics-classifying-economies-analytical-purposes
Fantom, N., & Serajuddin, U. (2016). The World Bank's classification of countries by income. Retrieved from http://documents.worldbank.org/curated/en/408581467988942234/pdf/WPS7528.pdf
Feinson, S. (2003). National innovation systems overview and country cases. Retrieved from https://cspo.org/legacy/library/110215F7ST_lib_KnowledgeFlowsVo.pdf#page=13
Feynman, R. P. (1959). *Plenty of room at the bottom*. Retrieved from https://web.pa.msu.edu/people/yang/RFeynman_plentySpace.pdf
Fillis, I., & Rentschler, R. (2010). The role of creativity in entrepreneurship. *Journal of enterprising culture, 18*(01), 49-81.
Flynn, H., Hwang, D., & Holman, M. (2013). Nanotechnology update: Corporations up their spending as revenues for nano-enabled products increase. *Lux Executive Summit* Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/20163/flynn_nanotechnology.pdf?sequence=1&isAllowed=y
Fontana, R., Nuvolari, A., Shimizu, H., & Vezzulli, A. (2013). Reassessing patent propensity: Evidence from a dataset of R&D awards, 1977–2004. *Research Policy, 42*(10), 1780-1792.
Framework, E. (2013). What is the purpose of medical research? *The Lancet, 381*(9864), 347.

Francke, E., & Alexander, B. (2019). Entrepreneurial development in South Africa through innovation: A model for poverty alleviation. *Acta Commercii, 19*(1), 1-11.
FRB. (2004). 2004-2005 Essay contest - Why are some countries rich and some countries poor? Retrieved from https://www.minneapolisfed.org/community/financial-and-economic-education/student-essay-contest/essay-contest-topics/2004-2005-essay-contest---why-are-some-countries-rich-and-some-countries-poor#top
Freeman, C. (1989). *Technology policy and economic performance: Lessons from Japan*. London: Pinter Publishers.
Fujii, H., & Managi, S. (2017). Decomposition analysis of water treatment technology patents. *Water, 9*(11), 860.
Fuller, D. B. (2009). Reinvigorating Hong Kong's innovation system: An overview of Hong Kong Innovation Project. Retrieved from http://savantas.org/wp-content/uploads/2014/06/overview.pdf
Gallup, J. L., Sachs, J. D., & Mellinger, A. D. (1999). Geography and economic development. *International regional science review, 22*(2), 179-232.
GEDI. (2017). The entrepreneurial ecosystem of South Africa: A strategy for global leadership 2017. Retrieved from https://sabcms.blob.core.windows.net/wp-content/2017/03/GEDI-South-Africa-Analysis2.pdf
Geiger, R. L., & Sá, C. M. (2008). *Tapping the riches of science: Universities and the promise of economic growth*. Cambridge: Harvard University Press.
Gerschenkron, A. (1962). *Economic backwardness in historical perspective: A book of essays*. New York: Praeger.
Ghazinoory, S., & Farazkish, M. (2010). A model of technology strategy development for Iranian nano-composite companies. *Technological and Economic Development of Economy, 16*(1), 25-42.
Gholizadeh, H., Naeini, A. B., & Moini, A. (2015). A quantitative model of technological catch-up. *International Journal of Engineering & Technology, 4*(1), 233-243.
Gidhwani, D. (2015). Procurement and training practices of selected dairy units in Gujarat. Retrieved from https://shodhganga.inflibnet.ac.in/bitstream/10603/76404/10/10_chapter%201.pdf
Giesen, E., Riddleberger, E., Christner, R., & Bell, R. (2010). When and how to innovate your business model. *Strategy & Leadership, 38*(4), 17-26.
Glass, A. J. (2010). Imitation as a stepping stone to innovation. Retrieved from http://ggl.rieb.kobe-u.ac.jp/coe/seminar/kobe_workshop2006/Amy_Glass.pdf
Glen, S. (2014). Statistical analysis: Definition, examples. Retrieved from https://www.statisticshowto.com/statistical-analysis/
Golichenko, O. (2016). The national innovation system: From concept to research methodology. *Problems of Economic Transition, 58*(5), 463-481.
Graham, S. J., & Iacopetta, M. (2014). Nanotechnology and the emergence of a general purpose technology. *Annals of Economics and Statistics/Annales D'Économie et de Statistique*(115/116), 25-55.
Grant, R. M. (1997). The knowledge-based view of the firm: implications for management practice. *Long range planning, 30*(3), 450-454.
Gressmann, A., Mondragon, Y. B., & Bacigalupo, D. (2018). *Critical review of the relevance and reliability of data sources, methods, parameters and determining factors to produce market studies on manufactured*

nanomaterials on the EU market. Retrieved from https://euon.echa.europa.eu/documents/23168237/24095696/170718_critical_review_of_market_studies_nanomaterials_final_report_en.pdf/ec77f39e-0918-5984-d7b1-654e3b1f14da

Groboljšek, B., Ferligoj, A., Mali, F., Kronegger, L., & Iglič, H. (2014). The role and significance of scientific collaboration for the new emerging sciences: The case of Slovenia. *Teorija in praksa, 51*(5), 864-883.

Grübler, A. (1991). Diffusion: long-term patterns and discontinuities. *Technological Foresting and Social Change, 39*, 159- 180.

Guimón, J. (2013). Promoting university-industry collaboration in developing countries. *World Bank.* Retrieved from https://www.researchgate.net/publication/278961909_Promoting_university-industry_collaboration_in_developing_countries_Innovation_Policy_PlatformOECD_and_World_Bank/link/5587eab408aeb0cdade0edd9/download

Gupta, N., Healey, D., Stein, A., & Shipp, S. (2013). Innovation policies of South Korea. Retrieved from https://www.wilsoncenter.org/sites/default/files/IDA%20Document%20D-4984%20FINAL%20Korea%20Innovation%20Policies.pdf

Guston, D. H. (2010). *Encyclopedia of nanoscience and society* (Vol. 2). London: SAGE Publications.

Halaweh, M. (2013). Emerging technology: What is it. *Journal of technology management & innovation, 8*(3), 108-115.

Haller, A.-P. (2012). Concepts of economic growth and development challenges of crisis and of knowledge. *Economy Transdisciplinarity Cognition, 15*(1), 66.

Hao, S., & Yu, B. (2011). The impact of technology selection on innovation success and organizational performance. *Ibusiness, 3*(4), 366-371.

Harack, B. (2010). What is the ladder of economic development? Retrieved from https://www.visionofearth.org/news/what-is-the-ladder-of-economic-development/

Harding, C. (2010). Integrate to innovate. *Construction Research and Innovation, 1*(2), 14-19.

Harrison, D. (2009). An overview of health and health care in South Africa 1994–2010: Priorities, progress and prospects for new gains. Retrieved from http://linux.bhfglobal.com/files/bhf/overview1994-2010.pdf

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

Hart, T., Jacobs, P., & Mhula, A. (2013). Rural innovation assessment tool (riat) concept paper series. Retrieved from http://www.hsrc.ac.za/uploads/pageContent/4338/RIAT2012_ConPaper3-Policy%20Review%2029%20July%202013%20FINAL2.pdf

Hartono, A. (2015). Developing new ideas & capability-based framework for innovation process: Firm analysis for Indonesia. *Procedia-Social and Behavioral Sciences, 169*, 161-169.

Hayter, R., & Edgington, D. W. (2004). Flying geese in Asia: The impacts of Japanese MNCs as a source of industrial learning. *Tijdschrift voor Economische en Sociale Geografie, 95*(1), 3-26.

Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change, 74*(4), 413-432.

Henderson, R., & Cockburn, I. (1994). Measuring competence? Exploring firm effects in pharmaceutical research. *Strategic management journal, 15*(1), 63-84.
Henri, C., & Wim, M. (2000). *The National Innovation System of Belgium*. Berlin: Springer-Verlag.
HESA. (2012). Promoting higher education - industry partnerships and collaborations: A report to the research and innovation strategy group higher education South Africa. Retrieved from http://www.usaf.ac.za/wp-content/uploads/2017/08/Promoting-Higher-Education_Industry-Partnerships_2012.pdf
Hobday, M. (1994). Export-led technology development in the four dragons: The case of electronics. *Development and Change, 25*(2), 333-361.
Holister, P. (2002). *Nanotechnology: The tiny revolution*. Retrieved from https://www.nanotech-now.com/CMP-reports/NOR_White_Paper-July2002.pdf
Hossain, M. M. (2020). Current status of global research on novel coronavirus disease (COVID-19): A bibliometric analysis and knowledge mapping. F1000Research 9 (374), 1-12.
HRD-SA. (2009). Human resource development strategy for South Africa (HRD-SA) 2010 – 2030. Retrieved from https://www.gov.za/sites/default/files/gcis_document/201409/doehrds-sa22022010.pdf
Huang, C., Notten, A., & Rasters, N. (2011). Nanoscience and technology publications and patents: a review of social science studies and search strategies. *The Journal of Technology Transfer, 36*(2), 145-172.
Huang, C., & Wu, Y. (2012). State-led technological development: A case of China's nanotechnology development. *World Development, 40*(5), 970-982.
Hullmann, A., & Meyer, M. (2003). Publications and patents in nanotechnology. *Scientometrics, 58*(3), 507-527.
IBM. (2008). Global CEO study:The enterprise of the future. Retrieved from https://www.ibm.com/ibm/ideasfromibm/ae/en/ceo/20080505/index3.shtml
IBM. (2010). People are your most valuable asset Retrieved from https://www.oracle.com/assets/ibm-oracle-chro-294764.pdf
Iddris, F. (2015). The use of innovation capability and national innovation systems in promoting sustainable development: A conceptual analysis. *Journal of Sustainable Development in Africa, 17*(3), 116-127.
IFPMA. (2017). The pharmaceutical industry and global health: Facts and figures 2017. Retrieved from https://www.ifpma.org/wp-content/uploads/2017/02/IFPMA-Facts-And-Figures-2017.pdf
Islam, N., & Miyazaki, K. (2010). An empirical analysis of nanotechnology research domains. *Technovation, 30*(4), 229-237.
ISO. (2005). Nanotechnologies: ISO working definition ISO/TC 229 Retrieved from https://www.iso.org/committee/381983.html
Itika, J. (2011). *Fundamentals of human resource management: Emerging experiences from Africa*. Amsterdam: African Studies Centre.
IWGN. (2000). National nanotechnology initiative: Leading to the Next Industrial Revolution. Retrieved from https://clintonwhitehouse4.archives.gov/media/pdf/nni.pdf
Jaffe, A. B. (2015). Technology diffusion. Retrieved from https://doi.org/10.1002/9781118900772.etrds0328

Jamison, E. (1991). *World population profile: 1991* (0895-3341). Retrieved from Washington DC: https://www.census.gov/content/dam/Census/library/publications/1991/demo/wp-91.pdf

Jie, S. (2017). Seizing opportunities, Hong Kong's innovation and technology has a bright future. Retrieved from https://www.bochk.com/dam/investment/bocecon/SY2017032(en).pdf

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational researcher, 33*(7), 14-26.

Jovanovic, B., & Lach, S. (1997). Product innovation and the business cycle. *International Economic Review*, 3-22.

Kalaian, S. A., & Kasim, R. M. (2011). Longitudinal studies. In P. J. Lavrakas (Ed.), *Encyclopedia of Survey Research Methods*. Thousand Oaks: Sage Publications, Inc.

Kao, R. W. (1993). Defining entrepreneurship: past, present and? *Creativity and Innovation Management, 2*(1), 69-70.

Kaplan, D. (2004). South Africa's national research and development strategy: A review. *Science, Technology and Society, 9*(2), 273-294.

Katila, R. (2000). Using patent data to measure innovation performance. *International Journal of Business Performance Management, 2*(1/2/3), 180-193.

Kayal, A. A. (2008). National innovation systems a proposed framework for developing countries. *International Journal of Entrepreneurship and Innovation Management, 8*(1), 74-86.

Kemp, R., & Weehuizen, R. (2005). Policy Learning: What does it mean and how can we study it? Retrieved from https://nifu.brage.unit.no/nifu-xmlui/bitstream/handle/11250/226561/d15policylearning.pdf?sequence=1&isAllowed=y

Kenton, W. (2018). Window of opportunity. Retrieved from https://www.investopedia.com/terms/w/window-of-opportunity.asp

Khan, I., Saeed, K., & Khan, I. (2017). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry.* Retrieved from https://ac.els-cdn.com/S1878535217300990/1-s2.0-S1878535217300990-main.pdf?_tid=8d5459a0-8bcb-46cb-8272-ac079819e0a5&acdnat=1551641531_a23084b3199e5fc6953102c76645e8db

Khan, J., & Khattak, N. U. R. (2014). The significance of research and development for economic growth: The case of Pakistan. Retrieved from https://mpra.ub.uni-muenchen.de/59805/1/MPRA_paper_59805.pdf

Khanna, V. K. (2016). *Integrated nanoelectronics: Nanoscale CMOS, Post-CMOS and allied nanotechnologies*. New Dehli, India: Springer.

Khayyat, N. T., & Lee, J.-D. (2015). A measure of technological capabilities for developing countries. *Technological Forecasting & Social Change*(92), 210-223.

Khoza, S. (2018). Building human capital for the development of nanotechnology in South Africa. Retrieved from http://cms.capemedia.co.za/file/4d1b7ff18256222da645d0224c3467b2/Sizwe%20Khoza.pdf

Kim, L. (1980). Stages of development of industrial technology in a developing country: a model. *Research Policy, 9*(3), 254-277.

Kim, L. (1997). *Imitation to innovation: The Dynamics of Korea's technological Learning*. Cambridge, Massachusetts: Harvard Business Review Press.
Kim, L. (1998). Crisis construction and organizational learning: Capability building in catching-up at Hyundai Motor. *Organization science, 9*(4), 506-521.
King, K., & Fransman, M. (1984). *Technological capability in the third world*. London: Macmillan.
Kosacoff, B. (2013). Developing competing capabilities in the Argentian industry (1958 - 2008). In G. Dutrénit, K. Lee, R. Nelson, L. Soete, & A. Vera-Cruz (Eds.), *Learning, capability building and innovation for development*. New York: Palgravw Macmillan.
Kraemer-Mbula, E., & Wamae, W. (2010). *Innovation and the development agenda*. Ottawa: OECD.
Krammer, S. M. (2017). Science, technology, and innovation for economic competitiveness: The role of smart specialization in less-developed countries. *Technological Forecasting and Social Change, 123*, 95-107.
Kreuchauff, F., & Teichert, N. (2014). Nanotechnology as general purpose technology. Retrieved from https://pdfs.semanticscholar.org/c58b/6fbc3665155676ff73bd8d84b8f9b8da4dca.pdf
Krieger, M., Tao, D., & Royeen, C. B. (2016). Foundations of evidence-based gerontological occupational therapy practice. In K. F. Barney, C. Emerita, & M. A. Perkinson (Eds.), Occupational therapy with aging adults. Amsterdam: Elsevier B.V.
Kumar, A. (2014). Nanotechnology development in India: an overview. Retrieved from http://www.ris.org.in/images/RIS_images/pdf/DP%20193%20Amit%20Kumar.pdf
Kumar, S. (2010). Building research capacity in allied health: New decade, new challenges and new opportunities. *Internet Journal of Allied Health Sciences and Practice, 8*(2), 3.
Labonte, M. (2010). The 2007-2009 recession: Similarities to and differences from the past. Retrieved from http://www.au.af.mil/au/awc/awcgate/crs/r40198.pdf
Lall, S. (1992). Technological capabilities and industrialization. *World Development, 20*(2), 165-186.
Landes, D. S. (2015). *Wealth and poverty of nations: Why some are so rich and some so poor* New York: W. W. Norton & Company.
Lee, K. (2005). Making a Technological Catch-up: Barriers and opportunities. *Asian Journal of Technology Innovation, 13*(2), 97-131.
Lee, K. (2013). *Schumpeterian analysis of economic catch-up: Knowledge, path-creation, and the middle-income trap*. Cambridge: Cambridge University Press.
Lee, K. (2016). *Economic catch-up and technological leapfrogging: The path to development and macroeconomic stability in Korea*. Cheltenham, Gloucester: Edward Elgar Publishing.
Lee, K. (2019). *The art of economic catch-up: Barriers, detours and leapfrogging in innovation systems*. Cambridge: Cambridge University Press.
Lee, K., Gao, X., & Li, X. (2016). Industrial catch-up in China: a sectoral systems of innovation perspective. *Cambridge Journal of Regions, Economy and Society, 10*(1), 59-76.

Lee, K., Im, B., & Han, J. (2017). The national innovation system (NIS) for the catch-up and post-catch-up stages in South Korea. In H.-j. Kwon & M. G. Koo (Eds.), *The Korean government and public policies in a dvelopment nexus*. New York: Springer.

Lee, K., & Ki, J.-h. (2017). Rise of latecomers and catch-up cycles in the world steel industry. *Research Policy, 46*(2), 365-375.

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

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

Lee, K., & Malerba, F. (2018). Economic catch-up by latecomers as an evolutionary process. In R. Nelson (Ed.), *Modern Evolutionary Economics*. Cambridge: Cambridge University Press.

Lee, K., & Mathews, J. (2013). Science, technology and innovation (STI) for sustainable development Retrieved from http://www.keunlee.com/modules/board/bd_download_db.html?id=eng_research_book&no=1809

Lee, K., Song, J., & Kwak, J. (2015). An exploratory study on the transition from OEM to OBM: Case studies of SMEs in Korea. *Industry and Innovation, 22*(5), 423-442.

Lee, S., & Bozeman, B. (2005). The impact of research collaboration on scientific productivity. *Social studies of science, 35*(5), 673-702.

Leitch, C. M., & Harrison, R. T. (1999). A process model for entrepreneurship education and development. *International Journal of Entrepreneurial Behavior & Research, 5*(3), 83-109.

Levin, K. A. (2006). Study design III: Cross-sectional studies. *Evidence-based dentistry, 7*(1), 24-25.

Li, H., Zhao, X., Zheng, P., Hu, M., Lu, Y., Jia, F., & Tong, X. (2015). Classic citations in main primary health care journals: A PRISMA-compliant systematic literature review and bibliometric analysis. *Medicine, 94*(49), e2229.

Li, K., Rollins, J., & Yan, E. (2018). Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis. *Scientometrics, 115*(1), 1-20.

Lin, J. Y. (2012). From flying geese to leading dragons: New opportunities and strategies for structural transformation in developing countries. *Global Policy, 3*(4), 397-409.

Lin, O. C. (1998). Science and technology policy and its influence on economic development in Taiwan. In H. S. Rowen (Ed.), *Behind East Asian Growth: The Political and Social Foundations of Prosperity* (Vol. 1, pp. 185). London Routledge.

Lipsey, R. G., Carlaw, K. I., & Bekar, C. T. (2005). *Economic transformations: General purpose technologies and long-term economic growth*. Oxford: Oxford University Press

Liu, F.-c., Simon, D. F., Sun, Y.-t., & Cao, C. (2011). China's innovation policies: Evolution, institutional structure, and trajectory. *Research Policy, 40*(7), 917-931.

Liu, L., & Zhang, J. (2007). Characterising nanotechnology research in China. *Science, Technology and Society, 12*(2), 201-216.

Liu, X. (2006). Path-following or leapfrogging in catching-up: The case of Chinese telecommunication equipment industry. Retrieved from http://wp.circle.lu.se/upload/CIRCLE/workingpapers/200701_Liu.pdf

Long, C. X., & Wang, J. (2019). China's patent promotion policies and its quality implications. *Science and Public Policy, 46*(1), 91-104.

Long, V. (2014). *A technological capabilities perspective on catching up: the case of the Chinese information and communications technology industry.* (PhD). KTH Royal Institute of Technology, Stockholm.

Lucas Jr, R. E. (1988). On the mechanics of economic development. *Journal of monetary economics, 22*(1), 3-42.

Lundvall, B.-Å. (2010). *National systems of innovation: Toward a theory of innovation and interactive learning* (Vol. 2). London: Anthem Press.

Maghrebi, M., Abbasi, A., Amiri, S., Monsefi, R., & Harati, A. (2011). A collective and abridged lexical query for delineation of nanotechnology publications. *Scientometrics, 86*(1), 15-25.

Mahmoudzadeh, M., & Alborzi, M. (2017). Modeling Iranian innovation network in nanotech for policy: applying an adopted version of SKIN model. *Journal of Science and Technology Policy Management, 8*(2), 129-145.

Makhoba, X., & Pouris, A. (2017). Bibliometric analysis of the development of nanoscience research in South Africa. *South African Journal of Science, 113*(11-12), 1-9.

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

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

Malherbe, J. B., Bhadeshia, H. K. D. H., & Field, J. E. (2009). Review report on centre of excellence in strong materials. Retrieved from https://www.nrf.ac.za/sites/default/files/documents/2009%20DST-NRF%20CoE%20in%20Strong%20Materials%20Review%20Report%20%28website%29.pdf

Mansoori, G. A., & Soelaiman, T. F. (2005). Nanotechnology—an introduction for the standards community. *Journal of ASTM International, 2*(6), 1-22.

Manuelli, R., & Seshadri, A. (2003). Frictionless technology diffusion: the case of tractors. Retrieved from https://www.nber.org/papers/w9604.pdf

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., & Marrs, A. (2013). *Disruptive technologies: Advances that will transform life, business, and the global economy*. San Francisco: McKinsey & Company

Manzini, S. T. (2012). The national system of innovation concept: An ontological review and critique. *South African Journal of Science, 108*(9-10), 1-7.

March, J. G. (1991). Exploration and exploitation in organizational learning. *Organization science, 2*(1), 71-87.

Maresova, P., Penhaker, M., Selamat, A., & Kuca, K. (2015). The potential of medical device industry in technological and economical context. *Therapeutics and clinical risk management, 11*, 1505=-1514.

Marimuthu, M., Arokiasamy, L., & Ismail, M. (2009). Human capital development and its impact on firm performance: Evidence from developmental economics. *Journal of international social research, 2*(8), 265-272.

Mariz-Pérez, R. M., Teijeiro-Alvarez, M. M., & Garcìa-Alvarez, M. T. (2012). The relevance of human capital as a driver for innovation. *Cuadernos de economia, 35*(98), 68-76.
Marshall, M. N. (1996). Sampling for Qualitative Research. Oxford: Oxford University Press.
Maselesele, M. S. (2011). *Managing the implementation of the assessment policy in the Senior Certificate Band.* (PhD). University of Pretoria, University of Pretoria. Retrieved from https://repository.up.ac.za/bitstream/handle/2263/25138/Complete.pdf?sequence=10&isAllowed=y
Mathews, J. A. (2002). Competitive advantages of the latecomer firm: A resource-based account of industrial catch-up strategies. *Asia Pacific journal of management, 19*(4), 467-488.
Mathews, J. A. (2006). Catch-up strategies and the latecomer effect in industrial development. *New political economy, 11*(3), 313-335.
Mathias, P. (2013). *The first industrial nation: The economic history of Britain 1700–1914*. New York: Routledge.
MBA. (2018). List of specialties, fields of specialty practice and related specialist titles. Retrieved from https://www.medicalboard.gov.au/documents/default.aspx?record=WD10%2F106&dbid=AP&chksum=07LyDUkqqYa5O5LXuqbSzg%3D%3D
McCaston, M. K. (2005). Tips for collecting, reviewing, and analyzing secondary data. *HLS Advisor, 27*, 1-9.
Mercer University School of Medicine (MUSM) (2020). Difference between PubMed, Embase, Web of Science and Scopus. Retrieved from https://med.mercer.edu/library/scopus-trial.htm
Metcalfe, S. (1995). The economic foundations of technology policy: Equilibrium and evolutionary perspectives. In P. Stoneman (Ed.), *Handbook of the Economics of Innovation and Technological Change*. Oxford: Blackwell Publishers.
Meyer, M. (2000). Patent citations in a novel field of technology: What can they tell about interactions between emerging communities of science and technology? *Scientometrics, 48*(2), 151-178.
Meyer, M. (2001). Patent citation analysis in a novel field of technology: An exploration of nano-science and nano-technology. *Scientometrics,, 51*(1), 163–183.
Mintek. (2018). The DST/MINTEK nanotechnology innovation centre 10 year anniversary. Retrieved from https://www.mintek.co.za/2018/04/23/minteks-nic-celebrates-10-years/
Mintek. (2019). The DST/Mintek nanotechnology innovation centre. Retrieved from https://www.nanoorbit.com/nanotechnology-companies/the-dst-mintek-nanotechnology-innovation-centre.html
Mkhize, H. (2017). University graduation numbers are on the rise - StatsSA. Retrieved from https://www.iol.co.za/business-report/university-graduation-numbers-are-on-the-rise-statssa-12109853
Moagi, D. (2002). South African national research and development strategy. Retrieved from https://www.pub.ac.za/wp-content/uploads/2015/06/sa_rd_strat_2002.pdf
Morris, L. (2008). Innovation metrics: The innovation process and how to measure it. *An InnovationLabs White Paper. InnovationLab. LLC.* Retrieved from http://www.innovationlabs.com/Measuring_Innovation.pdf

Mu, Q., & Lee, K. (2005). Knowledge diffusion, market segmentation and technological catch-up: The case of the telecommunication industry in China. *Research Policy, 34*(6), 759-783.
Mufamadi, S. (2016). South Africa needs to start to venture into nanotechnology commercialisation by employing sustainable models. Retrieved from https://www.npep.co.za/newsletter/issues/march-2016/south-africa-needs-to-start-to-venture-into-nanotechnology-commercialisation-by-employing-sustainable-models/
Muller, M., Schreiner, B., Smith, L., van Koppen, B., Sally, H., Aliber, M., Cousins, B., Tapela, B., Van der Merwe-Botha, M., & Karar, E. (2009). Water security in South Africa. Retrieved from https://www.dbsa.org/EN/About-Us/Publications/Documents/DPD%20No12.%20Water%20security%20in%20South%20Africa.pdf
Musee, N., Brent, A. C., & Ashton, P. J. (2010). A South African research agenda to investigate the potential environmental, health and safety risks of nanotechnology. *South African Journal of Science, 106*(3-4), 01-06.
Mytelka, L. (2004). Catching up in new wave technologies. *Oxford Development Studies, 32*(3), 389-405.
NACI. (2017). South African science, technology and innovation indicators. Retrieved from http://www.naci.org.za/wp-content/uploads/2018/07/South_African_Science_Technology_And_Innovation_Indicators_Report_2017.pdf
NACI. (2019). National advisory council on innovation. Retrieved from https://nationalgovernment.co.za/units/view/121/national-advisory-council-on-innovation-naci
Nadakavukaren, A. (2011). *Our global environment: A health perspective*. Long Grove, Illinois: Waveland Press, Inc.
Naidoo, R. (2002). *Corporate governance: An essential guide for South African companies*. Cape Town: Juta and Company Ltd.
Nani, G. V. (2016). Pioneer or imitate? An analysis of business imitations. *Problems and Perspectives in Management, 14*(3), 691-697.
NationalResearchCouncil. (2014). *Triennial review of the national nanotechnology initiative*. Washington, D.C.: National Academies Press.
Ndlovu, S. (2017). Presidential Address: Industry-academic collaborations-an opportunity for the minerals industry during the economic downturn. *Journal of the Southern African Institute of Mining and Metallurgy, 117*(9), 839-847.
Nelson, R. R. (1993). *National innovation systems: a comparative analysis*. Oxford: Oxford University Press.
Nibusinessinfo. (2019). Business growth through collaboration: Benefits of business collaboration. Retrieved from https://www.nibusinessinfo.co.uk/content/benefits-business-collaboration
Nicolaides, A. (2014). Research and Innovation–the drivers of economic development. *African Journal of Hospitality, Tourism and Leisure, 3*(2), 1-16.
Nielsen, E. (2008). Nanotechnology and its impact on consumers. Retrieved from https://www.consumerscouncil.com/site/consumers_council_of_canada/assets/pdf/Nanotech_report.pdf
Nielsen, L. (2011). Classifications of countries based on their level of development: How it is done and how it could be done. Retrieved from file:///C:/Users/a0009328/Downloads/_wp1131%20(1).pdf

Nieminen, P., Carpenter, J., Rucker, G., & Schumacher, M. (2006). The relationship between quality of research and citation frequency. *BMC Medical Research Methodology, 6*(1), 42.
Niosi, J., & Reid, S. E. (2007). Biotechnology and nanotechnology: science-based enabling technologies as windows of opportunity for LDCs? *World Development, 35*(3), 426-438.
NNI. (2000). National nanotechnology initiative: Leading to the next industrial revolution. *Microscale Thermophysical Engineering, 4*, 205–212.
NRF. (2014). Evaluation and rating: Key research areas and types of research output. Retrieved from https://www.nrf.ac.za/sites/default/files/documents/Key%20Research%20Areas%20and%20Types%20of%20Research%20Outputs%202014.pdf
NRF. (2015). Infrastructure funding instruments: National equipment programme (NEP) and national nanotechnology equipment programme (NNEP). Retrieved from https://www.nrf.ac.za/sites/default/files/documents/IFI%20Framework%202015-16%20-%20June%202015%20ns.pdf
NRF. (2018a). 2018 List of operating research chairs. Retrieved from https://www.nrf.ac.za/document/2018-list-operating-research-chairs
NRF. (2018b). National research foundation annual performance plan 2018/19–2020/21. Retrieved from http://pmg-assets.s3-website-eu-west-1.amazonaws.com/NRF_APP_2018-2019.pdf
Nuffic. (2015). Education system South Africa Retrieved from https://www.nuffic.nl/documents/489/education-system-south-africa.pdf
OECD. (1997). National innovation systems. Retrieved from https://www.oecd.org/science/inno/2101733.pdf
OECD. (1999). Managing national innovation systems. Retrieved from https://www.oecd-ilibrary.org/docserver/9789264189416-en.pdf?expires=1563620874&id=id&accname=ocid56029661&checksum=98F39BDC45B7605BEECE194AD698D098
OECD. (2001). The well-being of nations: The role of human and social capital Retrieved from http://www.oecd.org/site/worldforum/33703702.pdf
OECD. (2004). Patents and innovation: Trends and policy challenges. Retrieved from http://www.dklevine.com/archive/refs4122247000000000502.pdf
OECD. (2005). Guidelines for collecting and interpreting innovation data. Retrieved from https://www.oecd-ilibrary.org/docserver/9789264013100-en.pdf?expires=1531939357&id=id&accname=ocid56029661&checksum=8FECC2DF753A998A175EC0D91D30CAED
OECD. (2009). OECD patent statistics manual. *Francia: OECD Publications.* Retrieved from https://unstats.un.org/unsd/EconStatKB/Attachment553.aspx?AttachmentType=1
OECD. (2010). *The impacts of nanotechnology on companies: Policy insights from case studies*. Paris: OECD Publishing.
OECD. (2012). Innovation for development. Retrieved from https://www.oecd.org/innovation/inno/50586251.pdf
OECD. (2016). OECD science, technology and innovation outlook 2016. Retrieved from https://www.oecd-ilibrary.org/docserver/sti_in_outlook-2016-en.pdf?expires=1566573622&id=id&accname=ocid56029661&checksum=79E608F6D40E1DBFD489AB86F2594F05

OECD. (2019). Science, technology and patents. Retrieved from https://stats.oecd.org/
Okagbue, H. I., Opanuga, A. A., Oguntunde, P. E., Adamu, P. I., Iroham, C. O., & Adebayo, A. O. (2018). Research Output Analysis for Universities of Technology in Nigeria. *International Journal of Education and Information Technologies, 12*, 105-109.
Okpara, F. O. (2007). The value of creativity and innovation in entrepreneurship. *Journal of Asia entrepreneurship and sustainability, 3*(2), 1-14.
Olckers, C. (2011). *A multi-dimensional measure of psychological ownership for South African organisations.* (PhD). University of Pretoria.
Ouellette, L. L. (2015a). *Economic growth and breakthrough innovations: a case study of nanotechnology*. Retrieved from https://www.wipo.int/edocs/pubdocs/en/wipo_pub_econstat_wp_29.pdf
Ouellette, L. L. (2015b). Nanotechnology and innovation policy. *Harvard Journal of Law & Technology, 29*(1), 33-75.
Pack, H., & Nelson, R. R. (1999). The Asian miracle and modern growth theory. *The Economic Journal, 109* (457), 416-436.
Page, P. (2012). Research designs in sports physical therapy. *International journal of sports physical therapy, 7*(5), 482-492.
Pakes, T. (1998). Industrial development as an effective local economic development strategy: The Port Elizabeth metropole as a case study. *Unpublished paper presented at the Trade and Industrial Policy Secretariat Annual Forum, Muldersdrift.* Retrieved from http://www.tips.org.za/files/191.pdf
Pandza, K., Wilkins, T. A., & Alfoldi, E. A. (2011). Collaborative diversity in a nanotechnology innovation system: Evidence from the EU Framework Programme. *Technovation, 31*(9), 476-489.
Parente, S. L. (2008). Narrowing the economic gap in the 21st century. In R. H. Kim, E. J. Fulner, & M. A. O’Grady (Eds.), *2008 Index of Economic Freedom*. Washington: The Heritage Foundation and Dow Jones & Company.
Park, K.-H., & Lee, K. (2006). Linking the technological regime to the technological catch-up: analyzing Korea and Taiwan using the US patent data. *Industrial and corporate change, 15*(4), 715-753.
Parker, H. (2007). An analysis of buyer-supplier collaboration in the South African textile industry. *Professional Accountant, 7*(1), 207-217.
Patel, P., & Pavitt, K. (1994a). National innovation systems: why they are important, and how they might be measured and compared. *Economics of innovation and New Technology, 3*(1), 77-95.
Patel, P., & Pavitt, K. (1994b). The nature and economic importance of national innovation systems. *Science, Technology and Industry Review, 14*, 9-32.
PCSBI. (2010). New directions: The ethics of synthetic biology and emerging technologies. Retrieved from https://bioethicsarchive.georgetown.edu/pcsbi/sites/default/files/PCSBI-Synthetic-Biology-Report-12.16.10_0.pdf
Perez, C. (1988). New technologies and development. In C. Freeman & B. Lundvall (Eds.), *Small countries facing the technological revolution* (Vol. 85, pp. 97). London: Pinter Publishers.
Pérez, C. (2001). Technological change and opportunities for development as a moving target. *CEPAL Review, 75*, 109-130.

Perez, C., & Soete, L. (1988). Caatching up in technology: Entry barriers and windows of opportunity. In G. Dosi, C. Freeman, R. Nelson, G. Silverberg, & L. Soete (Eds.), *Technological Change and Economic Theory*. London: Pinter Publishers.

Perkel, J. (2016). Nanotechnology: The promises and pitfalls of science at the nanoscale. Retrieved from https://www.odomgroup.northwestern.edu/wp-content/uploads/2016/06/NanoTech.Final_.052316pdf.pdf

Perkins, R., & Neumayer, E. (2005). The international diffusion of new technologies: A multitechnology analysis of latecomer advantage and global economic integration. *Annals of the Association of American Geographers, 95*(4), 789-808.

Pihlajamaa, M., Patana, A., Polvinen, K., & Kanto, L. (2013). Requirements for innovation policy in emerging high-tech industries. *European Journal of Futures Research, 1*(1), 8.

Ployhart, R. E., & Vandenberg, R. J. (2010). Longitudinal research: The theory, design, and analysis of change. *Journal of management, 36*(1), 94-120.

Pogue, T. E. (2007). *Mobility of human resources and systems of innovation: a review of literature*. Cape Town: Human Sciences Research Council Press.

Poh, L. C. (2016). From research to innovation to enterprise: The case of Singapore. In S. Dutta, B. Lanvin, & S. Wunsch-Vincent (Eds.), *The Global Innovation Index 2016: Winning with global innovation* (pp. 133-139). Geneva: Cornell University, INSEAD, and WIPO

Pope, A., Bouxsein, P., Manning, F. J., & Hanna, K. E. (2001). *Innovation and invention in medical devices: workshop summary*. Washington DC: National Academies Press.

Popovici, O. C. (2017). International competitiveness versu location attractiveness for FDI: A theoretical approach. *Annals of'Constantin Brancusi'University of Targu-Jiu. Economy Series.* Retrieved from http://www.utgjiu.ro/revista/ec/pdf/2017-01/29_Popovici%20Oana.pdf

Popovici, O. C., & Călin, A. C. (2014). FDI theories. A location-based approach. *The Romanian Economic Journal, 17*(53), 3-24.

Porter, A. L., Youtie, J., Shapira, P., & Schoeneck, D. J. (2008). Refining search terms for nanotechnology. *Journal of Nanoparticle Research, 10*(5), 715-728.

Pouris, A. (2012). Technology trends: A review of technologies and policies. Retrieved from http://www.dti.gov.za/industrial_development/docs/Final_Technology_Trends.pdf

Pouris, A., Pouris, A., & Buys, A. (2012). Nanotechnology and biotechnology research in South Africa: Technology management lessons from a developing country. Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6304055

Preschitschek, N., & Bresser, D. (2010). Nanotechnology patenting in China and Germany-a comparison of patent landscapes by bibliographic analyses. *Journal of Business Chemistry, 7*(1), 3-13.

Radelet, S., & Sachs, J. (1997). Asia's reemergence. *Foreign Affairs, 76*, 44-59.

Radu, S. (2018). The big spenders in research and development. Retrieved from https://www.usnews.com/news/best-countries/articles/2018-11-09/these-countries-are-the-top-spenders-on-research-and-development

Rahman, M. S. (2016). The advantages and disadvantages of using qualitative and quantitative approaches and methods in language “Testing and Assessment” research: A literature review. *Journal of Education and Learning, 6*(1), 102.
Ramadani, V., & Gerguri, S. (2011). Innovations: principles and strategies. *Strategic Change, 20*(3-4), 101-110.
Ramadani, V., Gërguri, S., Rexhepi, G., & Abduli, S. (2013). Innovation and economic development: The case of FYR of Macedonia. *Journal of Balkan and Near Eastern Studies, 15*(3), 324-345.
Ramani, S. V., Chowdhury, N., Coronini, R., & Reid, S. E. (2011). On India's plunge into Nanotechnology: What are good ways to catch-up? *UNU-MERIT Working Paper Series.* Retrieved from http://collections.unu.edu/eserv/UNU:226/wp2011-020.pdf
Ramrathan, L. (2016). Beyond counting the numbers: Shifting higher education transformation into curriculum spaces. *Transformation in Higher Education, 1*(1), 1-8.
Rao, K. U., & Kishore, V. (2010). A review of technology diffusion models with special reference to renewable energy technologies. *Renewable and sustainable energy reviews, 14*(3), 1070-1078.
Rees, W. (2015). Economics vs. the Economy. Retrieved from https://www.greattransition.org/images/Rees-Economics-vs-Economy_1.pdf
FoodRisc (2016). Mixed methods research What is it?. Retrieved from http://resourcecentre.foodrisc.org/mixed-methods-research_185.html
Rizk, N., El Said, A., Weheba, N., & De Beer, J. (2018). *Towards an alternative assessment of innovation in Africa*. Retrieved from http://www.openair.org.za/wp-content/uploads/2018/02/WP-10-Towards-An-Alternative-Assessment-of-Innovation.pdf
Roco, M. C., Mirkin, C. A., & Hersam, M. C. (2011). Nanotechnology research directions for societal needs in 2020: Summary of international study. *Journal of Nanoparticle Research, 13*, 897–919.
Rodrik, D. (2007). *Introductiion to one economics, many recipes: Globalization, institutions, and economic growth*. Princeton, New Jersey: Princeton University Press.
Rogers, M. (1998). The definition and measurement of innovation. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.194.4269&rep=rep1&type=pdf
Rogerson, C. M. (2008). Tracking SMME development in South Africa: Issues of finance, training and the regulatory environment. *Urban Forum, 19*(1), 61-81.
Rosenbloom, J. L., Ginther, D. K., Juhl, T., & Heppert, J. A. (2015). The effects of research & development funding on scientific productivity: Academic chemistry, 1990-2009. *PloS one, 10*(9), e0138176.
Rotolo, D., Hicks, D., & Martin, B. (2015). What is an emerging technology? *Research Policy, 44*(10), 1827-1843.
RoyalSociety. (2004). Nanoscience and nanotechnologies: opportunities and uncertainties. Retrieved from https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2004/9693.pdf
Sá, C. (2015). *Perspective of Industry’s engagement with African Universities*. Retrieved from http://www.heart-resources.org/wp-content/uploads/2015/09/Report-on-University-Industry-Linkages.pdf

SA/BRICS. (2016). Memorandum of understanding between competition authorities of BRICS on cooperation in the field of competition law and policy. Retrieved from http://www.compcom.co.za/wp-content/uploads/2016/05/MoU-BRICS.pdf

SA/China. (2000). Memorandum of understanding between the government of the republic of South Africa and the government of the people's Republic of China on co-operation in the fields of wetland and desert ecosystems and wildlife conservation. Retrieved from https://www.environment.gov.za/sites/default/files/docs/wetlandanddesert_ecosystemsanwildlifeconservation.pdf

SA/Japan. (2003). South africa and Japan joint science and technology research collaboration. Retrieved from https://www.nrf.ac.za/sites/default/files/South%20Africa%20Japan%20%28JSPS%29%20Call%20Guideline.pdf

SA/Mozambique. (2014). Memorandum of understanding between the government of the republic of South Africa and the government of the republic of Mozambique on cooperation in the field of biodiversity conservation and management. Retrieved from https://www.environment.gov.za/sites/default/files/docs/sa_mozambique_mou_fieldofbiodiversity.pdf

SA/UK. (2003). Memorandum of understanding between the government of the United Kingdom of Great Britain and Northern Ireland and the government of the Republic of South Africa on the reciprocal educational exchange of healthcare concepts and personnel. Retrieved from https://assets.aspeninstitute.org/content/uploads/files/content/images/ghd/UK%20%E2%80%93%20South%20Africa%20MOU.pdf

Sachs, J. D. (2006). *The end of poverty: Economic possibilities for our time*. London: Penguin Books.

Sachs, J. D., Mellinger, A. D., & Gallup, J. L. (2001). The geography of poverty and wealth. *Scientific American, 284*(3), 70-75.

SAHRC. (2002). Right to health care. Retrieved from https://www.sahrc.org.za/home/21/files/Reports/4th_esr_chap_4.pdf

Saidi, T., & Douglas, T. S. (2017). Nanotechnology in South Africa-Challenges in evaluating the impact on development. *South African Journal of Science, 113*(7-8), 1-2.

Saidi, T., Fortuin, J., & Douglas, T. S. (2018). Nanomedicine for drug delivery in South Africa: A protocol for systematic review. *Systematic reviews, 7*(1), 154.

Salamanca-Buentello, F., Persad, D. L., Martin, D. K., Daar, A. S., & Singer, P. A. (2005). Nanotechnology and the developing world. *Public Library of Science: Medicine, 2*(5), 383-386.

Salar-García, M., & Ortiz-Martínez, V. (2019). Nanotechnology for wastewater treatment and bioenergy generation in microbial fuel cells. In R. Prasad & T. Karchiyappan (Eds.), *Advanced Research in Nanosciences for Water Technology* (pp. 341-362). Switzerland: Springer.

Sanyal, B. C., & Varghese, N. (2006). Research capacity of the higher education sector in developing countries. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000153116/PDF/153116eng.pdf.multi

Sargent, J. F. (2008). *Nanotechnology and US competitiveness: Issues and options*. Retrieved from http://research.policyarchive.org/19056.pdf

Sargent Jr, J. F. (2016). Nanotechnology: A policy primer. Retrieved from http://eprints.internano.org/2357/1/Nanotechnology_A_Policy_Primer-Congressional_Research_Service.pdf
Sarkar, S., & Beitollahi, A. (2009). An overview on nanotechnology activities in Iran. *Iranian Journal of Public Health, 38*(1), .65-68.
Sastry, R. K., Anshul, S., & Rao, N. (2013). Nanotechnology in food processing sector-An assessment of emerging trends. *Journal of food science and technology, 50*(5), 831-841.
Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research Methods for Business Students (5th edn)*. Guildford, Surrey, United Kingdom: Pearson Education.
Scerri, M. (2009). *The evolution of the South African system of innovation since 1916*. Newcastle upon Tyne, UK: Cambridge Scholars Publishing.
Scherer, F. M. (1986). *Innovation and growth: Schumpeterian perspectives*. Cambridge, Massachusetts: MIT Press.
Schmidt, M. (2019). Gross Domestic Product GDP, Gross National Product GNP, and Gross National Income GNI. Retrieved from https://www.business-case-analysis.com/gross-domestic-product.html#thepagetop
Scholes, R., Anderson, F., Kenyon, C., Napier, J., Ngoepe, P., Van Wilgen, B., & Weaver, A. (2008). Science councils in South Africa. *South African Journal of Science, 104*(11-12), 435-438.
Shea, C. M., Grinde, R., & Elmslie, B. (2011). Nanotechnology as general-purpose technology: empirical evidence and implications. *Technology Analysis & Strategic Management, 23*(2), 175-192.
Siddiqi, A. (2005). Patents and pharmaceutical drugs: The need for change. Retrieved from https://web.stanford.edu/group/journal/cgi-bin/wordpress/wp-content/uploads/2012/09/Siddiqi_SocSci_2005.pdf
Siebert, H. (2000). The paradigm of locational competition. Retrieved from https://www.econstor.eu/bitstream/10419/2472/1/318843021.PDF
Simate, G. S., Iyuke, S. E., Ndlovu, S., & Heydenrych, M. (2012). The heterogeneous coagulation and flocculation of brewery wastewater using carbon nanotubes. *Water research, 46*(4), 1185-1197.
Simate, G. S., Ndlovu, S., Iyuke, S. E., & Walubita, L. F. (2013). Biotechnology and nanotechnology: A means for sustainable development in Africa. In A. Gurib-Fakim & J. N. Eloff (Eds.), *Chemistry for Sustainable Development in Africa* (pp. 159-191). Berlin: Springer-Verlag.
Simate, G. S., & Yah, C. S. (2014). The use of carbon nanotubes in medical applications-is it a success story. *Occupational Medicine and Health Affairs, 2*(1), 147.
Singh, J., & Agrawal, A. (2009). Recruiting for ideas: A difference-in-differences approach for estimating the effect of mobility on access to an inventor's prior knowledge. *Management Science, 57*(1), 129–150.
Sirelkhatim, F., & Gangi, Y. (2015). Entrepreneurship education: A systematic literature review of curricula contents and teaching methods. *Cogent Business and Management, 2*(1), 1052034.
Smit, Y., & Watkins, J. (2012). A literature review of small and medium enterprises (SME) risk management practices in South Africa. *African journal of business management, 6*(21), 6324-6330.
Sohn, E., Chang, S. Y., & Song, J. (2009). Technological catching-up and latecomer strategy: A case study of the Asian shipbuilding industry. *Seoul Journal of Business, 15*(25-57).

Soldatenko, A. (2011). Current uses of nanotechnology Retrieved from http://www.unitar.org/cwm/sites/unitar.org.cwm/files/Lodz%20Presentation%20(Current%20uses%20%20of%20nanotechnology).pdf
Soldatenko, A. (2011). Current uses of nanotechnology. Retrieved from http://www.unitar.org/cwm/sites/unitar.org.cwm/files/Lodz%20Presentation%20(Current%20uses%20%20of%20nanotechnology).pdf
Solow, R. M. (1957). Technical change and the aggregate production function. *The review of Economics and Statistics, 39*(3), 312-320.
Soumonni, O. (2014). Book Review: Schumpeterian analysis of economic catch-up: Knowledge, path-creation, and the middle-income trap. *African Journal of Science, Technology, Innovation and Development and Change, 6*(2), 159-161.
Soumonni, O. (2016). Innovation in emerging technologies and socio-economic transformation in Africa: fallacy or foresight? *Africagrowth Agenda, 2016*(10), 18-22.
Sprunger, J. G. (2017). The benefits of engaging in collaborative research relationships. *Observer, 30*(10), 42-43.
Srinivasan, R. (2008). Sources, characteristics and effects of emerging technologies: Research opportunities in innovation. *Industrial Marketing Management, 37*(6), 633-640.
Srivastava, R. (2012). Developing countries and scientific collaboration in pharmaceuticals. Retrieved from https://warwick.ac.uk/fac/cross_fac/iatl/reinvention/archive/volume5issue1/
Stahl, B. C. (2011). What does the future hold? A critical view of emerging information and communication technologies and their social consequences. In M. Chiasson, O. Henfridsson, H. Karsten, & J. I. DeGross (Eds.), *Researching the Future in Information Systems* (pp. 59-76). Berlin: Springer.
StatNano. (2018). Nano science, technology and industry scoreboard. Retrieved from https://statnano.com/news/61446/10-Best-Universities-of-World-in-Nanotechnology
Stevens, C. (1997). Mapping innovation. *The OECD Observer*(207), 16-19.
Stupp, S. I. (2002). *Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative*. Washington DC: National Academies Press.
Surbhi, S. (2015). Difference between developed countries anddeveloping countries. Retrieved from https://keydifferences.com/difference-between-developed-countries-and-developing-countries.html
Szałucka, M. (2015). Does Location Really Matter? The Influence of the fdi Location on Enterprise Competitiveness: The Evidence from Polish Enterprises. *Managing Global Transitions: International Research Journal, 13*(2).
Tafreshi, G. H., Imani, M. N., & Ghashlag, P. M. (2013). Designing a Model for Research Productivity Evaluation of Faculty of District 2 of Islamic Azad University of Iran. *World Applied Sciences Journal, 21*(12), 1708-1720.
Taniguchi, N. (1974). *On the basic concept of nanotechnology.* Paper presented at the International Conference on Production Engineering, Part II, Tokyo.
Taskin, F., & Zaim, O. (1997). Catching-up and innovation in high-and low-income countries. *Economics letters, 54*(1), 93-100.
Thapa, P. (2013). *Understanding the Base of the Pyramid: Inclusive Innovation Context Analysis Framework.* (MSc in Management of Technology). Delft University of Technology,

Liang, G. (2010). Difference between Science Citation Index® (SCI) and Science Citation Index ExpandedTM (SCIE) databases. Retrieved from https://jmst.ntou.edu.tw/webdownload/SCIE_Letter.pdf
Tidd, J., & Bessant, J. (2014). *Strategic innovation management*. Singapore: John Wiley & Sons.
UNCTAD. (2019). Science, tchnology and innovation capacity development course - Module 1: Innovation, policy and development. Retrieved from https://unctad.org/en/PublicationsLibrary/dtlstictinf2019d1_en.pdf
UNESCO. (2010). UNESCO science report 2010: The current status of science around the world. Retrieved from http://uis.unesco.org/sites/default/files/documents/unesco-science-report-2010-the-current-status-of-science-around-the-world-en.pdf
UNESCO. (2016). Nanotechnology is a growing research priority. Retrieved from http://www.unesco.org/new/en/member-states/single-view/news/nanotechnology_is_a_growing_research_priority/
UNFCCC. (2015). Strengthening national systems of innovation to enhance action on climate change. Retrieved from https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TEC_documents/5be1bf880cc34d52a4315206d54a711b/60d1580f741a4bc783da5a00cf64a879.pdf
Vaggi, G. (2017). The rich and the poor: A note on countries' classification. *PSL Quarterly Review, 70*(279), 59-82.
van der Drift, S. (2014). Innovation landscape in Singapore Retrieved from https://www.rvo.nl/sites/default/files/2014/06/Singapore%20Innovation%20Landscape.pdf
Van Elkan, R. (1996). Catching up and slowing down: Learning and growth patterns in an open economy. *Journal of International Economics, 41*(1-2), 95-111.
Van Ness, P. H., Fried, T. R., & Gill, T. M. (2011). Mixed methods for the interpretation of longitudinal gerontologic data: Insights from philosophical hermeneutics. *Journal of mixed methods research, 5*(4), 293-308.
Van Noorden, R. (2017). The science that's never been cited. *Nature, 552*(7684), 162-164.
Varnai, P., Rentel, M., Davé, A., De Scalzi, M., Timmerman, W., Rosemberg-Montes, C., & Simmonds, P. (2017). *The impact of collaboration: The value of UK medical research to EU science and health*. Retrieved from London: https://www.cancerresearchuk.org/sites/default/files/main_report_v8.pdf
Verbeek, A., Debackere, K., Luwel, M., & Zimmermann, E. (2002). Measuring progress and evolution in science and technology – I: The multiple uses of bibliometric indicators. *international Journal of management reviews, 4*(2), 179-211.
Verspagen, B., & Kaltenberg, M. (2015). Catching-up in a globalised context: Technological change as a driver of growth. *UNIDO-MERIT Working Papers.* Retrieved from https://www.unido.org/api/opentext/documents/download/9928041/unido-file-9928041
Vértesy, D. (2017). Preconditions, windows of opportunity and innovation strategies: Successive leadership changes in the regional jet industry. *Research Policy, 46*(2), 388-403.
Veugelers, R. (2014). The contribution of academic research to innovation and growth. Retrieved from

https://www.econstor.eu/bitstream/10419/125727/1/WWWforEurope_WPS_no071_MS65.pdf
Veugelers, R. (2017). The challenge of China's rise as a science and technology powerhouse. Retrieved from http://bruegel.org/wp-content/uploads/2017/07/PC-19-2017.pdf
Vidic, F. (2013). Dynamic learning and creativity in entrepreneurship. Retrieved from https://www.g-casa.com/conferences/slovenia/papers/Vidic.pdf
Walwyn, D. (2006). The South African national system of innovation: Structures, polices and performance. Retrieved from http://www.naci.org.za/wp-content/uploads/pdf/NACI%20Resources%20studies,%20reports%20and%20publications/2006/NACI%20Resources%20Studies%20etc.%20National%20system%20of%20innovation%202006.pdf
Wang, J.-H. (2007). From technological catch-up to innovation-based economic growth: South Korea and Taiwan compared. *The Journal of Development Studies, 43*(6), 1084-1104.
Warner, E. (2014). *Patenting and innovation in China: Incentives, policy, and outcomes.* (PhD). Pardee RAND Graduate School, Pardee RAND Graduate School. Retrieved from https://www.rand.org/content/dam/rand/pubs/rgs_dissertations/RGSD300/RGSD347/RAND_RGSD347.pdf
Weale, A. R., Bailey, M., & Lear, P. A. (2004). The level of non-citation of articles within a journal as a measure of quality: A comparison to the impact factor. *BMC Medical Research Methodology, 4*(1), 14.
Wedekind, V. (2013). NSC pass requirements: A discussion document for Umalusi on the NSC Pass mark. Retrieved from https://www.umalusi.org.za/docs/research/2013/nsc_pass.pdf
WEF. (2019). Health and Healthcare in the fourth industrial revolution: Global future council on the future of health and healthcare 2016-2018. Retrieved from http://www3.weforum.org/docs/WEF__Shaping_the_Future_of_Health_Council_Report.pdf
Westerlund, F. (2011). Russian nanotechnology R&D: Thinking big about small scale science Retrieved from https://www.foi.se/rest-api/report/FOI-R--3197--SE
Whitfield, L. (2012). How countries become rich and reduce poverty: A review of heterodox explanations of economic development. *Development Policy Review, 30*(3), 239-260.
WHO. (2008). Health and development. Retrieved from https://www.who.int/hdp/en/
Wilkinson, A. (2017). *Strategies to Promote Entrepreneurship: A comparative overview of strategies implemented in South Africa, India and Brazil.* (BCom Honours). The Independent Institute of Education, Rosebank College, Retrieved from http://iiespace.iie.ac.za/bitstream/handle/11622/203/Wilkinson.pdf?sequence=1&isAllowed=y
WISE. (2017). Collaboration, skills development, unique experiences - Key to cape winelands tourism growth. Retrieved from https://news.wine.co.za/news.aspx?NEWSID=31576
Wits. (2019). Wits universitystrategic plan for research: 2018-2022 Retrieved from https://www.wits.ac.za/research/
Wolla, S. A. (2017). Why are some countries rich and others poor? Retrieved from https://files.stlouisfed.org/files/htdocs/publications/page1-econ/2017/09/01/why-are-some-countries-rich-and-others-poor_SE.pdf

Wong, C.-Y., & Goh, K.-L. (2015). Catch-up models of science and technology: a theorization of the Asian experience from bi-logistic growth trajectories. *Technological Forecasting and Social Change, 95*, 312-327.
Wong, P. K. (1999). National innovation systems for rapid technological catch-up: An analytical framework and a comparative analysis of Korea, Taiwan and Singapore. Retrieved from https://core.ac.uk/download/pdf/51181670.pdf
Wong, P. K., Ho, Y. P., & Chan, C. K. (2007). Internationalization and evolution of application areas of an emerging technology: The case of nanotechnology. *Scientometrics, 70*(3), 715-737.
Woolworth. (2017). A collaboration between the Department of Trade and Industry, Woolworths and the IDC sees doors opening for black women entrepreneurs. Retrieved from https://www.polity.org.za/article/woolworths-a-collaboration-between-the-department-of-trade-and-industry-woolworths-and-the-idc-sees-doors-opening-for-black-women-entrepreneurs-2017-05-19
WorldBank. (2008). *Global economic prospects: Technology diffusion in the developing world*. Washington DC: World Bank.
WorldBank. (2018). New country classifications by income level: 2018-2019. Retrieved from http://blogs.worldbank.org/opendata/new-country-classifications-income-level-2018-2019
WorldBank. (2019). Research and development expenditure (% of GDP). Retrieved from https://tcdata360.worldbank.org/indicators/GB.XPD.RSDV.GD.ZS?country=ZAF&indicator=2013&countries=BRA&viz=line_chart&years=1996,2015
WRC. (2018). The South African water innovation story. Retrieved from http://www.wrc.org.za/wp-content/uploads/mdocs/TT%20743%20web.pdf
Wright, T. L. (2018). *Examining the Issue of compliance with personal protective equipment among wastewater workers across the southeast region of the United States.* (PhD). Georgia Southern University, Georgia Southern University. Retrieved from https://digitalcommons.georgiasouthern.edu/cgi/viewcontent.cgi?article=2969&context=etd
Wu, J. (2015). Fueling innovation: The role of R&D in economic growth. Retrieved from https://www.innovationfiles.org/fueling-innovation-the-role-of-rd-in-economic-growth/
Wu, X. (1992). *Secondary innovation process: Theory and pattern.* (PhD). Zhejiang University,
Wu, X., & Fan, Z. (2010). National innovation systems for China and India: an analytical framework and a comparative analysis. *International Journal of Learning and Intellectual Capital, 7*(2), 145-166.
Wu, X., Ma, R., Shi, Y., & Rong, K. (2009). Secondary innovation: The path of catch-up with 'Made in China'. *China economic journal, 2*(1), 93-104.
Wu, X., Ma, R., & Xu, G. (2006). Secondary innovation: The experience of Chinese enterprises in learning, innovation and capability building. Retrieved from https://smartech.gatech.edu/bitstream/handle/1853/36267/SECONDARY%20INNOVATION(Prof.%20WU%20Xiaobo).pdf
Yah, C., Simate, G., & Iyuke, S. (2012). Nanoparticles toxicity and their routes of exposures. *Pakistan journal of pharmaceutical sciences, 25*(2), 477-491.
Yang, J. (2012). Innovation capability and corporate growth: An empirical investigation in China. *Journal of Engineering and Technology Management, 29*(1), 34-46.

Yifan, D. (2009). Mechanisms for improving economic and industrial growth in developing countries. In T. Teng & D. Yifan (Eds.), *Environment and Development* (Vol. 1, pp. 305-320). London: EOLSS Publishers.

Yoon, C., Lee, K., Yoon, B., & Toulan, O. (2017). Typology and success factors of collaboration for sustainable growth in the it service industry. *Sustainability, 9*(11).

Young, E. (2015). The importance of research in healthcare. *South Sudan Medical Journal, 8*(4), 90-91.

Yusuf, S. (2012). From technological catch-up to innovation: The future of China's GDP growth. Retrieved from https://openknowledge.worldbank.org/bitstream/handle/10986/12781/701780ESW0p1170na008181100for0SIC0.pdf;sequence=1

Zhang, Z., Jin, J., & Guo, M. (2017). Catch-up in nanotechnology industry in China from the aspect of process-based innovation. *Asian Journal of Technology Innovation, 25*(1), 5-22.

Zhao, F., Zhao, Y., & Wang, C. (2008). Activities related to health, environmental and societal aspects of nanotechnology in China. *Journal of Cleaner Production, 16*(8-9), 1000-1002.

Zitt, M., & Bassecoulard, E. (2006). Delineating complex scientific fields by an hybrid lexical-citation method: An application to nanosciences. *Information processing & management, 42*(6), 1513-1531.

Zulu, M. (2018). *Review of the performance of Zambia's national system of innovation for the period 2001 to 2010.* (Master's degree). University of Cape Town, Retrieved from https://open.uct.ac.za/bitstream/handle/11427/28124/thesis_com_2018_zulu_mercy.pdf?sequence=1