J Nanopart Res (2021) 23: 92
https://doi.org/10.1007/s11051-021-05193-6

RESEARCH PAPER

A nanotechnology-foresight perspective of South Africa

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Received: 23 July 2020 / Accepted: 21 March 2021 / Published online: 13 April 2021

Abstract This paper presents a foresight perspective of nanotechnology in South Africa based on a 20-year period scientometric analysis of the country's nanotechnology publications on the Web of Science (WoS) Core Collection. Firstly, publication trends are reported; then, possible socio-economic relevant sectors arising from this information are determined. Lastly, indicators that can be used in foresight exercises to evaluate the potential nanotechnology research areas in South Africa are examined. The 20-year review is also compared with the recent past year, 2019, to identify any changing trends. South Africa's nanotechnology publications per year grew exponentially from 68 papers in 2000 to 1672 in 2019, an increase of 2459%. The total share of nanotech publications increased from 1.4% in 2000 to 6.6% in 2019, thus a 0.52% increase per year. Compared with Brazil, Russia, India and China, the BRICS countries, South Africa has the lowest nanotechnology productivity with an activity index of 0.68. Over the last 5 years, South Africa nanotech publications had a Hirsch-index of 94 and an average citations rate of 12.76 per paper. Universities are the most prominent publishers, and there are very few publications from the private sector, which can negatively impact the commercialisation of nanotechnology research. The top 10 most prolific researchers, author or co-author over 20% of the nanotechnology papers are reported. A mixture of old and new top researchers' names suggests succession planning in the system as the years progress. The emergence of computer science as one of the top 20 subjects publishing in nanotech in 2019 and a high level of researcher collaboration suggests possible convergence of nanotech, information technology and artificial intelligence in South Africa. The strategic socio-economic-focused nanotechnology research areas identified for South Africa include material science, photoluminance and optics, medicine, catalysis, electronics, energy, biotech, magnetism, sensors, water and communicable diseases. The top collaborating countries, top researchers, top institutions and nanotechnology

This article is part of the topical collection on Nanotechnology Convergence in Africa

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economic hubs are reported for each strategic research area. The level of innovation was evaluated using the nanotechnology value chain, and there is a meagre 3.5% of papers reporting on nano-enabled products.

Keywords Technology foresight · Nanotechnology · Scientometrics · Tech-mining · Innovation · Nanotechnology value chain

Introduction

Scientific innovations create value by developing new products and services, providing solutions to social problems, creating new enterprises and jobs, thereby improving the quality of life. Nanotechnology is an extremely disruptive emerging field of science dedicated to the study and manipulation of characteristics of matter at the atomic level, where the onset of size-dependent phenomena usually enables novel applications (Karpagam et al. 2011; Robinson et al. 2007; Salerno et al. 2008). Discoveries from nanoscience have a vast range of socio-economic benefits and significantly contribute to humanity's achieving the Sustainable Development Goals (SDGs). For example, discoveries from nanotechnology are providing solutions for affordable clean water (Mamba et al. 2007; Mwabi et al. 2011), efficient solar cells for renewable energy (Banin et al. 2020) and medical solutions, for example, nano-assisted face masks in destroying COVID-19 pathogens (De Sio et al. 2021). In addition, because of its multidisciplinary and interdisciplinary nature, plus the use of nanoscale building blocks (atoms and molecules), nanotechnology has become the core for the convergence of several disciplines (Roco and Bainbridge 2002; Salerno et al. 2008);

From a business and economic perspective, nanotechnology-enabled commercial products are increasing at an exponential rate (Islam and Miyazaki 2009), such that by 2013, the nano-enabled product's market was already over US$1 trillion (NSF 2014) and expected to reach US$3 trillion while contributing 6 million jobs by 2020 (Roco 2017). Hence, various scholars argue that nanotechnology will underpin the next Schumpeterian wave of world economic development (Linton and Walsh 2008; Mangematin and Walsh 2012; Tuncel 2015). As a result, many governments worldwide have positioned themselves to benefit from nanotechnology by implementing national nanotechnology initiatives. Countries that have implemented national nanotech strategies include the United States of America (USA), United Kingdom (UK), Japan, India, South Korea, Germany and South Africa, among others (Ali and Sinha 2014; Grassian et al. 2016; Miyazaki and Islam 2007; Roco et al. 2011).

Nanotechnology is a broad general purpose technology with applications in any field imaginable. To ensure limited resources are prudently utilised, countries or businesses cannot invest in nanotech across the board, but they have to select and focus on critical strategic nanotech research areas that possess the most significant potential to bring socio-economic development, competitiveness and return on investment (Connell et al. 2001; Lee and Song 2007; Shen et al. 2010). Hence, foresight methodologies must be utilised to identify key research areas to focus on and concentrate on (Salerno et al. 2008). Technology foresight is defined as the process of systematically considering the longer-term future of science, technology, economy and society to identify the key strategic research areas and those emerging generic technologies with the highest potential to result in socio-economic development (Martin 1995). Hence, technology foresight exercises must form an integral part of any research and development strategic plan to help identify critical technologies and R&D areas with the highest potential to support socio-economic development (Firat et al. 2008).

Technology foresight versus technology forecasting

The terms technology foresight and technology forecasting are sometimes used intangibility and to mean the same contextual principal and construct; this is evident when scholars define these terms, list their drivers, goals and methods that can be used to accomplish both. However, (Martin 2001) contends that scholars must note that foresight is different from technology forecasting. He argues that technology forecasting assumes that there is one unique future. Thus, in technology forecasting, the planner should predict future technology as accurate as possible. However, in technology foresight, one assumes that there are numerous possibilities for the future, and future technologies depend on planning choices. This research, therefore, uses the term technology foresight.

Foresight epistemology

There are two broad epistemological approaches to foresight studies, the positivism and interpretive approaches.

The positivism or realist epistemology of foresight argues that knowledge of the future is based on analysis of the past and present, which is then extrapolated into the future. It is in this school of thought that quantitative methods of foresight are based, for example, methods such as scanning the environment using publications in scientometrics, statistical techniques and extrapolation to estimate the future. Under this argument, Von Wright (2009) proposed the Laplace's Demon, a hypothetical observer which, based on its perfect knowledge, could predict the exact future state of the world (Von Wright 2009). However, Kalle and Rafael (Kalle and Rafael 2015) argue that predicting the future based on knowledge of past and present is probabilistic and uncertain at best because one can never be sure that the structure of the world does not change within the period of interest; thus, one can only estimate the future subject to limitations that follow from the assumptions for the extrapolation (Kalle and Rafael 2015).

The other school of thought in foresight studies is that given by Hideg (Hideg 2007) as quoted in (Kalle and Rafael 2015), who state that, "… the future is interpreted as something that already exists in the present in the thoughts and emotions of people. … Future thoughts are forming and reforming in the process of discourses, so the futures existing in the present are open and humanly constructed". Hence, Kalle and Rafael (2015) argue that the future already exists in the thoughts and emotions of people. It is from this school of thought that the qualitative approaches to foresight are based. Thus, one can use various forms of interviews like expert interviews and Delphi, brainstorming, creative workshops, wild cards, among others in trying to understand ideas and images of the future already existing in people's minds to gain knowledge about the future.

Scientometrics and technology foresight

Scientometrics is the study of the quantitative aspects of science utilising scientific documents such as academic journal publications, patents and policies (Jacobs 2010; Leydesdorff and Milojevic 2012). Scientometrics is traditionally utilised in Research Development and Innovation Evaluation Studies and to compare individual researchers, institutions or country performance among other evaluations. Several researchers have used scientometric studies to study the state of nanotechnology research in different countries (Hullman and Meyer 2003; Islam and Miyazaki 2010; Karpagam et al. 2011; Marinova and McAleer 2002; Tanaka 2013). Scientometrics was previously used to study the state of nanotechnology research in South Africa (Makhoba and Pouris 2017; Pouris 2007). However, this research used a different publications search strategy, covers a period of 20 years and focuses on nanotechnology foresight perspective.

Scientometrics can also be used as a foresight tool. The justification for the use of scientometrics in foresight studies is that publications data is an intermediate measure of innovation because science innovations start from basic science research (where publications are produced) that feeds the applied sciences and technological disciplines. Scientometrics use scientific publications data to capture innovation, research and development activities closer to basic science research, while patent data highlight activities closer to the commercialisation stage. The nanotechnology value chain can also be used to evaluate the state of maturity of nanotechnology research systems.

The advantage of scientometrics use in foresight studies was given by Lee (2008) and Santo et al. (2006) (de Miranda et al. 2006) who note that one of the most critical aspects of scientometrics analysis is that it goes beyond the experts' biases, enabling the discovery of facts and trends not perceived due to the limit of knowledge or prejudiced visions of experts. However, the use of scientometrics in foresight studies is very low, and this is supported by empirical evidence from research done by Popper (2008), where it was observed that out of 886 foresight studies done worldwide, scientometrics (bibliometrics) use constituted only 2.4% (Popper 2008). Also, no nanotechnology foresight research has been published since the establishment of the South Africa nanotechnology strategy. Thus, there is a need to improve and add to the literature on the use of scientometrics in technology foresight method and the nanotechnology foresight for South Africa.

In this study, the positivism, empirical and realist epistemology of foresight is followed because there are many publications on nanotechnology that can be analysed to study the past, the present, estimate the trends and extrapolate into the future. Thus, scientometric analysis was used to give a foresight perspective of the South African nanotechnology research landscape.

Methodology

Scientometric analysis was carried out through tech-mining utilising the Vantage Point Software. Tech-mining is the application of text mining tools to science and technology structured databases informed by technological innovation processes to produce Science Technology and Innovation (STI) indicators for decision making. Tech-mining uses the power of computers to analyse all documents (patents and publications) that are found in an area under investigation as compared with experts who are forced to sample a few publications to give a summary (Mikova and Sokolova 2014; Porter and Cunningham 2005).

A 20-year scientometric analysis of South African nanotechnology publications was done using data obtained from the Web of Science Core Collection. Porter et al. (2008) developed a modularised Boolean approach to defining nanotechnology, and the strategy was further refined by Arora et al. (2013). This search strategy was adapted and utilised to search and retrieve nanotechnology publications for analysis. Publications from 2000 to 2019 were analysed. The year 2000 was chosen as the starting period because that is when nanopublications began an exponential growth (Islam and Miyazaki 2009).

Vantage Point software does both basic and advanced scientometric functions that help elicit relationships among data fields such as authors, research fields, topics about which they write, their organisations, citations, collaborations, time series analysis among others (Porter and Cunningham 2005). Data analysis followed three logical steps. Step 1 involved clustering records into nanotechnology research areas, thus determining possible key research areas. Step 2 involved tabulating the size-dependent indicators of each research area, for example, counting the number of publications per research field and finally calculating normalised size-independent scientometric indicators for each research field.

Validity and reliability

The following precautions were taken to ensure the validity and reliability of the tech-mining results of this research. First, a well-established Boolean nanotechnology search strategy (Porter et al. 2008) was adapted to extract target records for analysis from the Web of Science core collection. Also, data cleaning was carried out to validate that the search strategy yielded high recall while balancing precision in extracting the nanotechnology-specific records for analysis.

Secondly, a large sample of papers, 11,265, was analysed, thereby reducing sampling error. Sampling error is more prevalent where the sample of objects being measured is very small; in this case, the sample used was substantial.

Results and discussion

This study aimed to use tech-mining to develop a foresight perspective of nanotechnology in South Africa using nanotechnology publications over the last 20 years, from 2000 to 2019.

The first step in foresight is scanning the research environment and understanding the major science and technology developments, including the major research area and alternatives. The second step of the foresight process is identifying key stakeholders who can be consulted in developing the identified research area for South Africa. The third step of foresight is the generation phase, where identified research areas are evaluated and analysed, and favourable futures that can support socio-economic development are identified. The above three steps of foresight are reported below.

Nanotechnology publications trend in South Africa

Table 1 below summarises South Africa's nanotechnology publication trend between 2000 and 2019. Publications per year increased from 68 in 2000 to 1672 in 2019, which is an increase of 2458%. The country's total publications, on the other hand, increased from 4950 in 2000 to 25,163 in 2019, which is an increase of 508%. Thus, nanotechnology research publications grew at a faster rate than other areas, and this relative growth is further explained by Fig. 1 below.

Figure 1 above shows that the total share of nanotechnology publications increased from 1.4% in 2000 to 6.6% in 2019, thus a 0.52% increase per year.

South Africa nanotechnology output in comparison with BRICS countries

The world's five major emerging economies, namely Brazil, Russia, India, China, and South Africa, form a grouping named the BRICS. South Africa's performance in nanotechnology was compared with that of BRICS countries using the nanotechnology activity index. The activity index (AI) is defined as the ratio of the

Table 1 South Africa's nanotechnology publications relative to total publications on WoS

Year	Nanotech publications	Total publications	Nanotech share %	Annual nanotech growth %
2000	68	4950	1.4%	
2001	83	4979	1.7%	22%
2002	84	5384	1.6%	1%
2003	96	5156	1.9%	14%
2004	135	5767	2.3%	41%
2005	163	6062	2.7%	21%
2006	170	6955	2.4%	4%
2007	245	8138	3.0%	44%
2008	276	8931	3.1%	13%
2009	337	9881	3.4%	22%
2010	417	10,218	4.1%	24%
2011	476	11,686	4.1%	14%
2012	628	13,652	4.6%	32%
2013	726	14,104	5.1%	16%
2014	830	15,422	5.4%	14%
2015	983	20,044	4.9%	18%
2016	1199	21,982	5.5%	22%
2017	1289	22,946	5.6%	8%
2018	1388	23,782	5.8%	8%
2019	1672	25,163	6.6%	20%
Total	11,265	245,202		

country's share in the publication output in the field to the country's share in the world's publication outputs in all fields (Rousseau 2018). The world activity index is considered to be one (1); hence, the AI for country X over period P can be approximated by equation (1) below.

$$\text{AI (nano, country X)} = \frac{\text{Country X ratio of nanopublications in period P}}{\text{World ratio of nanopublications in period P}} \quad (1)$$

Table 2 shows the comparison of South Africa to BRICS countries for 20 years as well as a 1-year snapshot. The results indicate that over the 20-year period from 2000 to 2019, South Africa had the lowest productivity in nanotechnology with an activity index of 0.68. China, with an activity index of 2, is the most productive country among the BRICS countries. However, when a single year (2019) is considered, the picture is almost the same South Africa was second from the bottom with an AI of 0.78. China and India remained at the top in terms of country activity index. From a foresight perspective, it means South Africa can benefit from collaborating with the more productive BRICS countries, benchmark and understand how South Africa can also improve to achieve comparable nanotechnology activity levels.

Nanotechnology publishing institutions in South Africa

Analysis of South Africa's most active nanotechnology research publishers is shown in Table 3 below. The results show that the majority of publishers are universities.

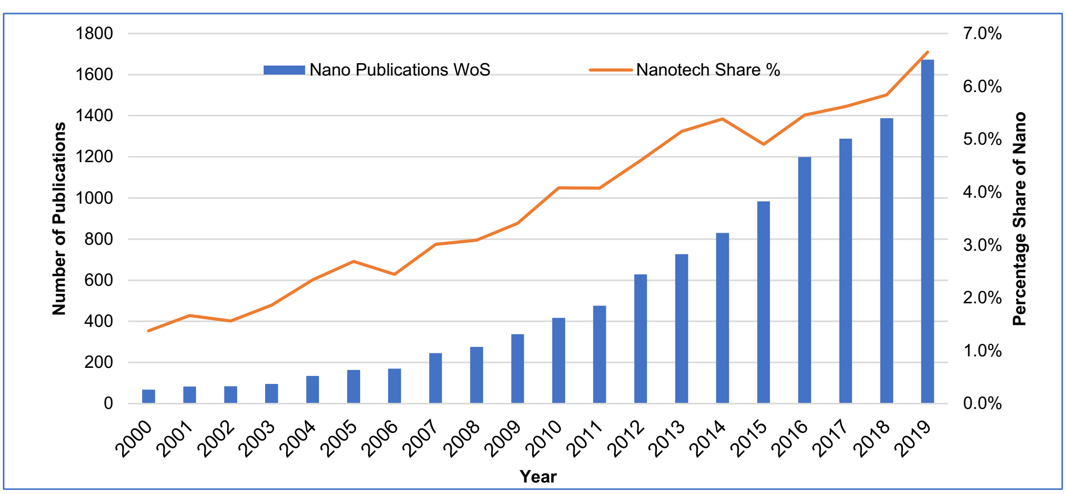

Fig. 1 Nanotechnology publication trend for South Africa

Table 2 SA nanotechnology publications compared with BRICS countries

20-year period 2000–2019					1-year period 2019				
Country	Nano publications	Total WoS	Nano ratio	Activity index	Country	Nano publications	Total WoS	Nano ratio	Activity index
World	2,718,619	40,331,494	0.067	1.00	World	260,675	3,168,362	0.082	1.00
China	664,787	4,939,513	0.135	2.00	China	94,059	607,574	0.155	1.88
India	165,351	1,312,591	0.126	1.87	India	22,399	140,491	0.159	1.94
Russia	93,394	876,138	0.107	1.58	Russia	9447	91,764	0.103	1.25
Brazil	45,656	874,857	0.052	0.77	Brazil	5211	87,818	0.059	0.72
South Africa	11,264	245,202	0.046	0.68	South Africa	1672	26,190	0.064	0.78

Table 3 Major nanotechnology publication contributors in South Africa

20-year period 2000–2019			1-year period 2019		
Institutions	Publications	Share %	Institutions	Publications	Share %
1) South Africa	11 264	100%	South Africa	1672	100%
2) University of Johannesburg	1583	14%	University of Johannesburg	355	21%
3) University of Witwatersrand	1370	12%	University of KwaZulu Natal	242	14%
4) University of KwaZulu Natal	1286	11%	University of South Africa	202	12%
5) Council Scientific & Industrial Research (CSIR)	1044	9%	National Research Foundation (iThembaLABS)	165	10%
6) University of Pretoria	959	9%	University of Witwatersrand	152	9%
7) University of Free State	940	8%	University of Pretoria	134	8%
8) University of Stellenbosch	905	8%	University of The Free State	129	8%
9) University of South Africa	867	8%	Tshwane University of Technology	118	7%
10) National Research Foundation (iThembaLABS)	789	7%	Council Scientific & Industrial Research (CSIR)	116	7%
11) University of Cape Town	748	7%	University of the Western Cape	105	6%
12) Rhodes University	665	6%	North West University South Africa	92	6%
13) University of the Western Cape	642	6%	University of Stellenbosch	80	5%
14) Tshwane University of Technology	494	4%	University of Cape Town	79	5%
15) North West University	492	4%	Rhodes University	62	4%
16) Nelson Mandela University	327	3%	Durban University of Technology	56	3%
17) University of Zululand	260	2%	Nelson Mandela University	55	3%
18) Durban University of Technology	206	2%	University of Zululand	42	3%
19) Vaal University of Technology	174	2%	Vaal University of Technology	33	2%
20) University of Fort Hare	142	1%	University of Fort Hare	31	2%
21) Cape Peninsula University of Technology	121	1%	University of Limpopo	19	1%
22) MINTEK	87	1%	University of Venda	17	1%
23) University of Limpopo	82	1%	Cape Peninsula University of Technology	16	1%
24) University of Venda	75	1%	Sefako Makgatho Health Sciences University	11	1%
25) SASOL Technology	24	0.21%	National Institute of Theoretical Physics (NITheP)	11	1%

Over a 20-year analysis period, the most prolific publisher is the University of Johannesburg, contributing 14%, followed by the University of the Witwatersrand with 12% and in third place is the University of KwaZulu Natal with 11%. The second group of publishers are national research facilities comprising only three institutions, namely the Council for Scientific and Industrial Research (CSIR), iThembaLABS, and MINTEK. The CSIR is the most prolific national facility in the fourth position, producing 9% of the publications, iThembaLABS and MINTEK had 7% and 1% of nanotechnology publications, respectively.

Only a single private company, SASOL-technology, was identified with 24 publications, a 0.21% contribution to the total output. This observation shows a lack of participation of the private sector in nanotechnology research, and from a foresight perspective, this will impact the innovation and commercialisation of nanotechnology research. This suggests a need to engage more private sector companies to be involved in nanotechnology research from a foresight planning perspective.

When the 1-year snapshot is considered, the top publishers over 20 years remained mostly unchanged. The University of South Africa, iThembaLABS and Tshwane University of Technology show that they have increased their nanotechnology activity. However, during the same period, the WITS university changed from 3rd to 6th position, and the CSIR went down from 5th position to 10th position.

Five-year Hirsch-index of South Africa nanotechnology publications

A key scientometric indicator obtained from publication analysis is the Hirsch-index (H-index) used to quantify a scientist's published research impact (Hirsch 2005). The H-index discounts for the disproportionate weight of highly cited publications and papers not yet cited. The H-index is determined from the list of an individual/institution's publications ranked in descending order by the number of times cited. H-index is equal to the number of papers (N) in the list that has N or more citations. The H-index or its modified version, the 5-year H-index denoted H5-index, is now used as a de facto tool for assessing individual researchers, universities, research institutions and even journals (Karpagam et al. 2011).

In order to evaluate the immediate impact of nanotechnology publications from South African institutions, the 5-year Hirsch-index (H5-index) was evaluated for the top ten publishing institutions in the last 5 years (2015–2019). Over the last 5 years, South Africa nanotechnology publications have a combined H5-index of 94 and an average citations rate of 12.76 per paper. During the same period, the top ten publishing institutions produced papers with an H5-index in the range 58 to 32. The average citation was 16.17 to 10.46, as shown in Table 4 below.

Researchers publishing in South Africa

Table 5 below shows the top ten researchers in terms of papers they either authored or co-authored for nanotechnology publications for South Africa. According to data on the WoS core collection between 2000 and 2019, there was a total of 30 614 authors/co-authors who wrote the 11,265 nanotechnology-related publications. However, the top ten researchers shown below together contributed 21.35% of publications. When the single year 2019 is considered, the result shows the top 10 researchers also contributed 20.39% of total publications. This result is inline Lotka's law (Phillips 2013) which state that the distributions of science and technology publications is highly skewed such that the leaders tend to be extremely prolific, while the rest occur in "ones and twos."

The single-year snapshot shows that the top 4 authors remained the same people. However, there are new names coming top in the 1-year, 2019 analysis. The emergence of new top authors suggested that new

Table 4 H5-index for top ten South Africa nanotechnology publishing institutions 2015–2019

Institutions	H5-index	Average citations per item
South Africa	94	12.76
1. University of Johannesburg	58	16.17
2. University of South Africa	55	14.54
3. National Research Foundation (iThemba Labs)	45	15.55
4. Council Scientific & Industrial Research (CSIR)	44	14.88
5. University of KwaZulu Natal	43	10.89
6. University of Witwatersrand	40	11.21
7. University of Cape Town	39	15.92
8. University of Pretoria	38	11.66
9. University of Stellenbosch	34	13.22
10. University of Free State	32	10.46

Table 5 Top ten researchers (authors/co-author) for nanotechnology publications in South Africa

20-year period 2000–2019			1-year period 2019		
Researcher name	Number of publications	Share %	Researcher name	Number of publications	Share %
1) NYOKONG T	445	3.95%	1) MAAZA M	56	3.35%
2) SWART HC	388	3.44%	2) SWART HC	45	2.69%
3) MAAZA M	326	2.89%	3) NYOKONG T	39	2.33%
4) RAY SS	260	2.31%	4) RAY SS	34	2.03%
5) GUPTA VK	178	1.58%	5) VAN DER BRUGGEN B	34	2.03%
6) COVILLE NJ	172	1.53%	6) OLUBAMBI PA	33	1.97%
7) NTWAEABORWA OM	167	1.48%	7) KAVIYARASU K	27	1.61%
8) REVAPRASADU N	166	1.47%	8) EZEMA FI	26	1.56%
9) MAMBA BB	153	1.36%	9) DEJENE FB	25	1.50%
10) EBENSO EE	151	1.34%	10) MAMBA BB	22	1.32%
Total percentage contribution		21.35%	Total percentage contribution		20.39%

researchers/authors are coming into the system mixed with experienced authors who have been there for years. This mixture is essential in foresight planning because it demonstrates continuity, and it suggests some form of succession planning taking place within the nanotechnology system of South Africa.

South Africa international collaboration in nanotechnology

International collaboration was analysed from co-authorship between South Africa and other countries. Figure 2 shows the top 20 countries collaborating with South Africa. In the last 20 years, India was the largest collaborating partner for South Africa with 1241 (11%) publications, and the USA comes second with 919 (8.2%) publications. On the African continent, Nigeria is South Africa's largest collaborating partner with 585 (5.2%) publications.

When one considers just the year 2019, India remains the biggest collaborating partner for South Africa. However, in 2019, Nigeria was number 2, and another African country Botswana comes up in the top 20 collaborating countries at number 16, suggesting increasing inter Africa-collaboration in nanotechnology. Another observation is that the percentage of collaboration between South Africa and the BRICS countries increased in 2019 compared with the last 20 years. For example, in 2019, Russia now appears on the top 20 at number 17, but it did not appear on the top 20 for the last 20 years; this can be attributed to efforts made under the BRICS collaboration.

Subject area focus for nanotechnology in South Africa

The examination of subject areas was carried out using the subject area classification of Web of Science. Table 6 below shows the top 20 subject areas in which nanotechnology research is published in South Africa. The most prolific subject area is chemistry accounting for over 34%. The top four subject areas, namely chemistry, material science, physics and engineering, together account for 93.05% in the last 20 years and 95.34% in 2019.

When the 1-year snapshot is considered, one finds that computer science, which did not appear on the top 20 subjects, now appears on the list contributing 1.26% of publications in 2019. The emergence of computer science as one of the top 20 subjects publishing in nanotechnology suggests a convergence of nanotechnology and computing science, for example, in areas such as artificial intelligence (AI) system design and the drive towards the 4th Industrial Revolution (4IR). Nanotechnology publications from computer science can also be a sign of nanotechnology convergence (Roco 2020). However, additional investigations need to be done to ascertain the existence and extent of the fusion of nanotechnology, biotechnology, information technology, and cognitive sciences (NBIC) in South Africa.

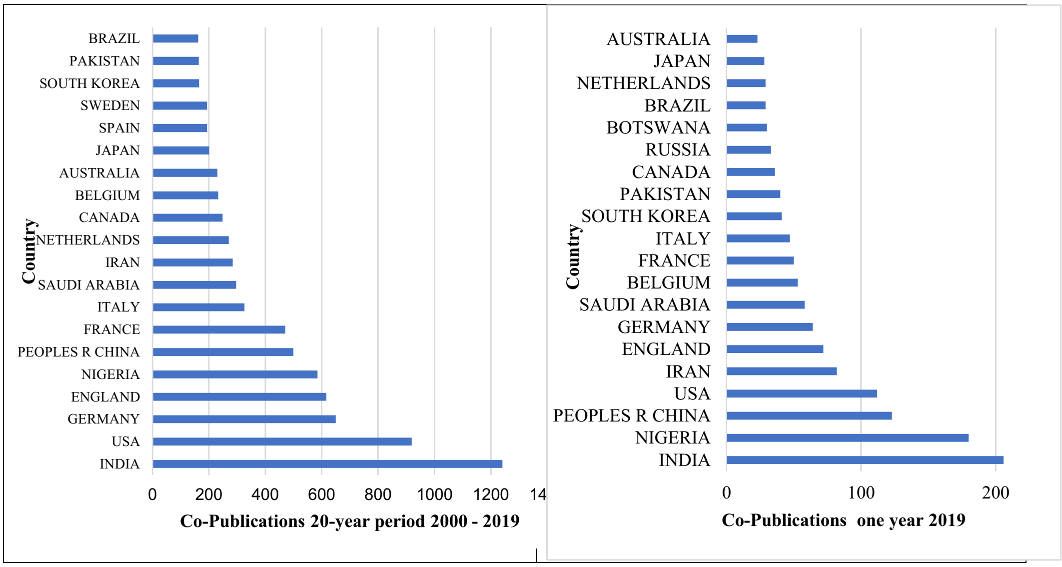

Fig. 2 Countries collaborating with South Africa in nanotechnology

Table 6 Top subject areas in which South Africa nanotechnology papers are published

20-year period 2000–2019			1-year period 2019		
Subject area	Publications	Share %	Subject area	Publications	Share %
1) Chemistry	3832	34.02	Chemistry	577	34.51
2) Materials Science	2733	24.26	Materials Science	434	25.96
3) Physics	2558	22.71	Physics	316	18.90
4) Engineering	1358	12.06	Engineering	308	18.42
5) Science Technology Other Topics	1259	11.18	Science Technology Other Topics	252	15.07
6) Electrochemistry	637	5.66	Electrochemistry	80	4.78
7) Polymer science	610	5.42	Environmental Sciences Ecology	75	4.49
8) Biochemistry Molecular Biology	464	4.12	Polymer Science	71	4.25
9) Optics	355	3.15	Energy Fuels	62	3.71
10) Environmental Sciences Ecology	354	3.14	Biochemistry Molecular Biology	59	3.53
11) Pharmacology Pharmacy	324	2.88	Pharmacology Pharmacy	59	3.53
12) Energy Fuels	291	2.58	Optics	46	2.75
13) Crystallography	277	2.46	Metallurgy Metallurgical Engineering	44	2.63
14) Metallurgy Metallurgical Engineering	253	2.25	Biotechnology Applied Microbiology	27	1.61
15) Biotechnology Applied Microbiology	216	1.92	Instruments Instrumentation	27	1.61
16) Water Resources	169	1.50	Thermodynamics	27	1.61
17) Instruments Instrumentation	161	1.43	Mechanics	25	1.50
18) Thermodynamics	145	1.29	Water Resources	23	1.38
19) Genetics Heredity	143	1.27	Crystallography	22	1.32
20) Biophysics	137	1.22	Computer Science	21	1.26

South Africa foresight research areas analysis

Technology foresight is the process of systematically considering the longer-term future of science, technology, economy and society to identify the key strategic research areas with the highest potential to result in socio-economic development (Martin 1995). Possible foresight research areas were generated from the analysis of South Africa's National Development Plan (NDP) Vision for 2030 (NPC 2011), the 10-Year National Innovation Plan (DST 2007) and the Nanotechnology Strategy 2005 (DST 2005). Combining these government policy requirements and nanotechnology subfields found in literature, the following possible socio-economic relevant research areas were identified, food, agriculture, automotive, cosmetics, mining, material science, energy, medicine, communicable diseases, electronics, photoluminance and optics, water, nanotools, sensors, catalysis, magnetism, biotechnology, nanofibers, nanofluids, textiles and engineering applications.

To identify if the above-mentioned research areas exist in the South African nanotechnology publications, one has to classify and categorise related research together. Unfortunately, as an emerging research area, the system of classifying nanotech research papers is not yet well established, there is no readily available lookup database for nanoscience research areas categorisation (Tanaka 2013). Tanaka (2013) proposed a system, but it is not comprehensive; it just gives basic science disciplines as categories, for example, nanophysics, nanochemistry and nanoengineering which is almost similar to WoS subject categorisation. An automatic nanotechnology publication categorising protocol was developed in Vantage Point utilising the thesaurus function and relevant keywords for each research area. This protocol was used to automatically group the South Africa publications into the foresight research area categories identified above. The system uses a one-to-many mapping such that a paper can fit into more than one research area, for example, a paper in energy discussing photovoltaics can at times fit into electronics and a biotechnology paper can at times also fit into medicine and communicable diseases.

Strategic foresight-based research areas

Table 7 below shows that for the last 20 years, the top research areas for South Africa's nanoscience were in Nanomaterials (25%), Photoluminance and Optics (19%) and Nano-Medicine (18%). Nanoscience research on water and communicable diseases only make up 3% and 2%, respectively. When a 1-year snapshot of the research areas is considered, one finds that there is no significant difference in the top research areas. However, in 2019, engineering applications of nanotechnology now come up the radar contributing 2% of publications in 2019.

The rest of the possible foresight research areas proposed above, such as food, textiles and automotive applications, had small ratios below 0.05%; hence, they will not be considered in this analysis.

South Africa research area experts

An essential step in any foresight process is mobilising and engaging key stakeholders who can be consulted in developing the identified research areas for South Africa. Table 8 below gives a summary of the top 10 nanotechnology experts against their number of publications per research area. The top publishing researcher per field has their number of publications highlighted by bold text; for example, the top publisher in Materials is Ray Suprakas; in medicine, it is Nyokong Tebello; while in electronics and energy, it is Maaza Malik; in water, it is Mamba Bhekie; in photoluminance and optics, it is Swart Hendrik. Nanotechnology foresight planners can use Table 8 to assemble a team of experts per field for further consultations.

South Africa research area institutions specialisations

In foresight, institutions are also part of the key stakeholders required in developing any selected research area. Table 9 shows the top publishing institution per research area. The most prolific publishing organisation is highlighted in bold text. For example, foresight planners can see that the top institutions for nanomedicine are the University of KwaZulu Natal, University of Witwatersrand and University of Cape Town. Alternately, they can also note that University of the Free state is the leading publisher in photoluminance and optics, and the University of Pretoria is the leading institution for nanoelectronics.

Table 7 Top research areas for South Africa

20-year period 2000–2019			1-year period 2019		
Nanotechnology research area	Number of publications	Ratio	Nanotechnology research area	Number of publications	Ratio
1) Materials	2845	25%	1) Materials	415	25%
2) Photoluminance & Optics	2172	19%	2) Photoluminance & Optics	367	22%
3) Medicine	2008	18%	3) Medicine	329	20%
4) Catalysis	1606	14%	4) Catalysis	287	17%
5) Electronics	1390	12%	5) Electronics	237	14%
6) Biotech	1021	9%	6) Biotech	194	12%
7) Energy	655	6%	7) Energy	135	8%
8) Magnetism	587	5%	8) Sensors	102	6%
9) Sensors	553	5%	9) Magnetism	99	6%
10) Water	328	3%	10) Water	79	5%
11) Communicable Diseases	243	2%	11) Engineering Applications	38	2%

South Africa research area international collaborators

International collaboration analysis is essential during foresight planning. Table 10 shows the top collaborating countries per research area using the number of papers the country co-authored with South Africa in the respective research area. The top collaborating countries per field are highlighted in bold text. India features as the top collaborating country in seven research areas; however, for medicine and communicable diseases, the top collaborating country is the USA, for energy China, and, for water Belgium.

South Africa nanotechnology research-clusters

A distinguishing feature of R&D activities is their agglomeration to specific regions rather than being evenly distributed within countries. This view is supported by Porter and Stern (2001), who argue that the physical location of R&D facilities is a significant factor that

Table 8 Top Ten South African nanoscience researchers in the identified research areas

South Africa Research Area	Researcher name									
	Nyokong. Tebello	Maaza. Malik	Swart. Hendrik C	Gupta. Vinod Kumar	Ray. Suprakas Sinha	Kasinathan. Kaviyarasu	Agarwal. Shilpi	Ntwaeaborwa. Odireleng M	Covill. Neville J	Mamba. Bhekie Brilliance
Materials	107	116	55	68	**150**	31	30	17	47	71
Photoluminance & Optics	87	185	**309**	25	47	56	13	149	15	13
Medicine	**98**	48	17	25	29	27	17	9	2	12
Catalysis	**123**	39	14	53	35	36	25	3	67	43
Electronics	30	**60**	26	4	27	9	3	8	21	11
Biotech	**35**	23	6	13	11	14	6	0	0	8
Energy	23	**45**	16	1	6	11	0	8	6	2
Magnetism	**41**	19	8	7	34	3	6	3	17	10
Sensors	**20**	18	11	19	7	7	7	4	7	10
Water	1	0	1	18	12	0	7	0	0	**36**

The top publishing researcher per research area is highlighted in bold text

Table 9 Institution focus research areas using the number of publications between 2000 and 2019

South Africa Research Area	Institution name							
	University of Johannesburg	University of Witwatersrand	CSIR	University of KwaZulu Natal	University of Free State	University of Stellenbosch	University of Pretoria	University of Western Cape
Materials	**555**	371	368	295	232	169	153	149
Catalysis	**348**	197	168	187	60	47	78	211
Photoluminance & Optics	262	232	230	192	**518**	52	128	111
Medicine	199	255	116	**276**	55	192	181	117
Electronics	190	203	131	147	122	64	**221**	66
Magnetism	120	68	54	**128**	33	89	19	16
Water	**116**	30	44	13	8	13	16	7
Biotech	112	128	71	**156**	30	94	90	62
Sensors	**102**	55	68	40	29	30	44	71
Energy	50	70	113	86	49	17	53	**121**
Communicable Diseases	5	40	19	44	5	**47**	29	11

South Africa Research Area	Institution name							
	University of Cape Town	University of South Africa	Tshwane University of Technol	North West University of	Rhodes University of	Nelson Mandela University	iThemba LABS	University of Zululand
Materials	92	257	186	118	171	100	87	103
Catalysis	91	168	42	80	142	20	49	16
Photoluminance & Optics	41	302	77	50	117	106	147	126
Medicine	240	96	65	103	170	36	41	23
Electronics	50	172	38	48	43	56	40	26
Magnetism	20	72	13	9	28	6	18	13
Water	6	53	62	11	8	6	1	4
Biotech	96	63	28	65	89	9	24	13
Sensors	26	51	29	19	45	10	12	11
Energy	21	62	26	27	31	21	34	14
Communicable Diseases	40	4	2	15	8	2	1	0

Top publishing institution per research area is highlighted in bold text

Table 10 Collaborating-country focus research areas using number of publications between 2000 and 2019

Area	India	USA	UK	China	Germany	Nigeria	France	Iran	Saudi Arabia	Italy	Belgium
Photoluminance & Optics	**363**	114	139	67	94	143	98	32	48	69	17
Materials	**323**	119	106	68	106	208	75	73	76	54	36
Catalysis	**200**	54	56	142	47	63	34	48	52	17	14
Medicine	193	**290**	170	62	129	70	95	37	56	47	52
Electronics	**136**	82	85	52	94	92	40	19	47	48	13
Magnetism	**116**	23	27	28	44	17	20	22	26	21	6
Biotech	**111**	103	71	30	44	41	25	21	24	19	15
Sensors	**78**	31	30	29	25	21	33	27	18	12	18
Energy	43	27	49	**87**	35	31	16	3	8	14	7
Water	30	33	14	28	5	17	2	22	11	2	**43**
Communicable Diseases	22	**77**	41	5	17	3	14	1	6	6	15

The top collaborating country per research area is highlighted in bold text

contributes to successful innovations. Certain areas present a competitive advantage in R&D innovations and commercialisation (Porter and Stern 2001). In economics, the geographic agglomeration of economic activity results in the improved technological or economic performance of the units involved (Peneder 1997). The economic benefits of technological agglomeration result from three major forces which are (1) knowledge spillovers between firms, e.g. sharing tacit knowledge; (2) local availability of specialised inputs and services from supporting industries; and (3) a geographically pooled labour market for specialised skills (Marshal 1920). Also, geographical proximity/clustering reduces operational costs for units involved (Fiedler and Welpe 2011).

In foresight planning, one needs to understand nanotechnology research clusters, including their research focus to be able to derive future innovation and commercialisation benefits linked to such clusters. A clustering system for nanotechnology institutions in South Africa was done using the country's main economic hubs and provinces. Table 11 shows the number of publications per research areas according to South Africa's nanotechnology research clusters. The top two clusters for a particular research area are

Table 11 South Africa nanotechnology clusters and research area focus 2000–2019

Area	Pretoria	Johannesburg	Western Cape	Free State	KwaZulu Natal	North West	Eastern Cape	Limpopo
Materials	865	**896**	571	242	452	145	237	38
Photoluminance & Optics	**692**	483	447	519	322	65	202	14
Medicine	414	457	**693**	55	342	121	189	41
Catalysis	394	**537**	440	104	221	105	135	22
Electronics	**504**	374	312	126	184	56	89	9
Biotech	225	240	**301**	30	202	73	90	24
Energy	**224**	116	209	50	102	36	46	24
Magnetism	135	174	**182**	38	145	12	32	8
Sensors	**163**	**163**	160	30	67	22	50	13
Water	**150**	140	45	10	30	12	12	11
Communicable Diseases	46	47	**101**	5	51	15	10	3

The top two research clusters per research area are highlighted in yellow

The top cluster per research area is highlighted in bold text

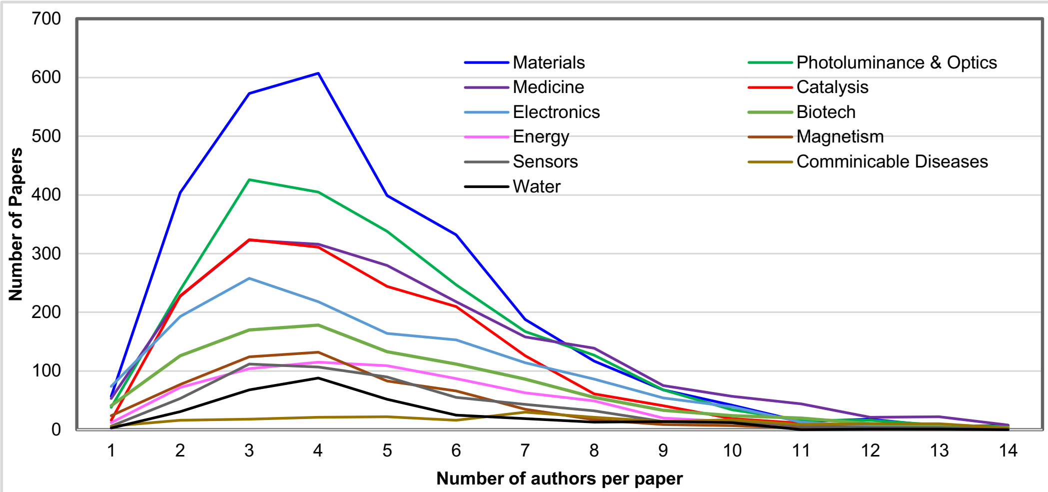

Fig. 3 Level of researcher collaboration per research area

highlighted and the most prolific cluster in bold text. Table 11 shows that if one needs to develop in photoluminance and optics, they need to locate either in Pretoria, or the Free State; for nanomedicine, they need be in the Western Cape or Johannesburg, and communicable diseases research in the Western Cape or KwaZulu Natal region.

South Africa research areas degree of collaboration

Cross-functional or interdisciplinary teams are viewed as one of the critical success factors for technological innovation (Connell et al. 2001; Torkkeli and Tuominen 2001). Interdisciplinarity in nanoscale research is one major thrust of science policymakers (Schummer 2004); for example, the USA Nanotechnology policy (Battard 2012) and the South Africa nanotechnology policy (DST 2005) both advocate for more interdisciplinary collaborations in nanotechnology research.

The extent or degree of collaboration can be measured by applying Subramanyam's formula (Subramanyam 1983), which states that the degree of collaboration C is a ratio between the number of multi-authored papers (NM) to the number of multi-authored papers (NM) plus the single authored (NS) ones as given in equation (2) below.

$$C = \frac{NM}{NM + NS} \tag{2}$$

where

- NM = number of multi-authored papers

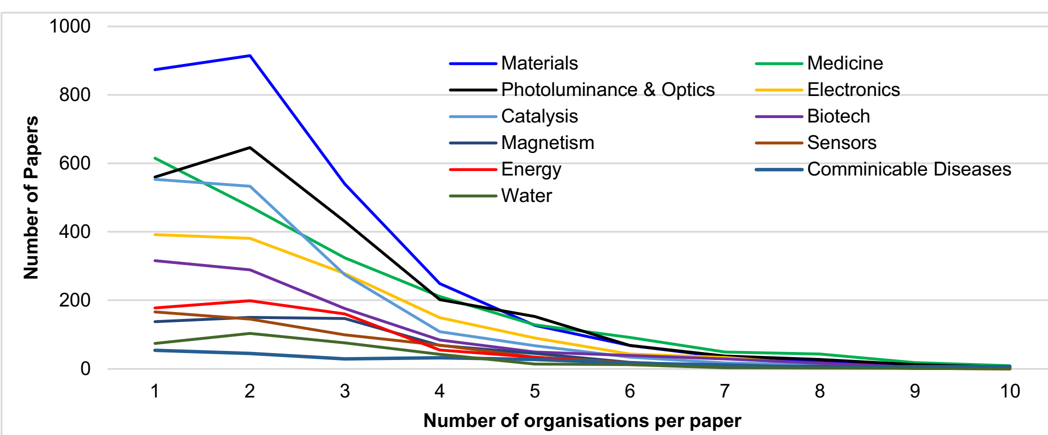

Fig. 4 Level of organisational collaboration per research area

Table 12 Degree of collaboration for research areas

Research area	Total number of papers	Single researcher authored papers	Single organisation authored papers	Researcher degree of collaboration	Organisational degree of collaboration
Materials	2845	57	874	0.98	0.69
Photoluminance & Optics	2172	38	560	0.98	0.74
Medicine	2008	53	615	0.97	0.69
Catalysis	1606	16	553	0.99	0.66
Electronics	1390	74	392	0.95	0.72
Biotechnology	1021	41	316	0.96	0.69
Energy	655	12	178	0.98	0.73
Magnetism	587	24	138	0.96	0.76
Sensors	553	6	166	0.99	0.70
Water	328	3	74	0.99	0.77
Communicable Diseases	243	6	54	0.98	0.78

- NS = number of single-authored papers

Collaboration in for South Africa's research areas was evaluated using co-authorship by authors and co-authorship by organisations. Figure 3 shows the level of co-authorship for the research areas. Only 2% of papers are single-author papers, the majority are by either 3 or 4 authors. The co-authorship distribution is bimodal; there are 19% papers with three authors and another 19% with four authors.

The degree of collaboration was further investigated using organisational co-authorship, as shown in Fig. 4 below. The level of organisational collaboration is lower than researcher collaboration. Most papers, 30%, are authored by researchers from a single organisation. The second-highest level is two organisations, and then, the collaboration falls exponentially such that at 10 organisations, there is only 0.05% of organisational co-authorship.

Table 12 below shows the level of collaboration, according to research areas and organisations. There is a high degree of collaboration between researchers varying from 0.95 to 0.99. However, there is a lower degree of collaboration among organisations varying between 0.69 and 0.78.

South Africa research area citation rates

The citation rates of the research areas were examined using citations per paper and relative citation rates. The average citation per nano-article for South Africa is 9.08 citations per paper (StatsNano 2020). This number was used to calculate the research area citation rate. Table 13

Table 13 Research area citations 2000–2019

Research area	Total citations	Number of papers	Citation per paper	Relative citation rate
Electronics	18,549	1390	13.3	1.47
Energy	10,449	655	16.0	1.76
Photoluminance & Optics	36,209	2172	16.7	1.84
Magnetism	10,313	587	17.6	1.93
Sensors	9964	553	18.0	1.98
Materials	52,593	2845	18.5	2.04
Catalysis	33,952	1606	21.1	2.33
Medicine	42,458	2008	21.1	2.33
Water	7013	328	21.4	2.35
Biotech	24,644	1021	24.1	2.66
Communicable Diseases	8203	243	33.8	3.72

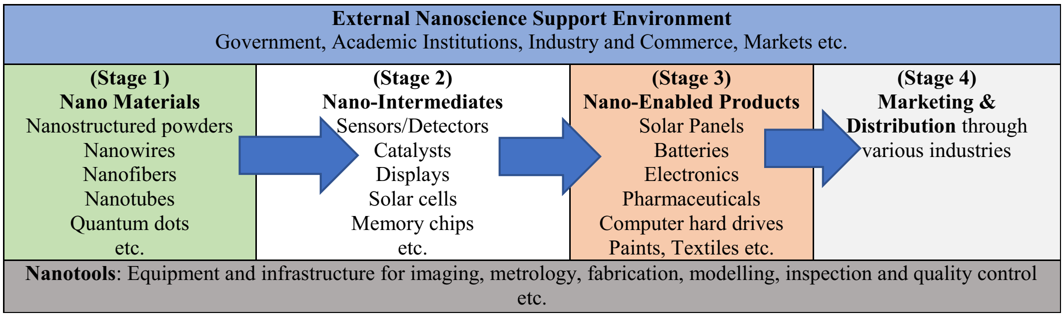

Fig. 5 Nanotechnology value chain

shows that electronics has the lowest citation rate at 13.3 citations per paper and communicable diseases have the highest citation rate of 33.8 citations per paper.

The nanotechnology value chain analysis for South Africa research areas

The transformation of nanotechnology inventions from ideation to commercialisation occurs in three main steps known as the nanotechnology value chain (Gkanas et al. 2013; Shapira et al. 2011; Wang and Guan 2012). Figure 5 below shows the key stages of the nanotechnology value chain. The nanotechnology value chain starts from nanomaterials, then moves to nano-intermediaries and finally nano-enabled products. The value chain enables decision-makers and foresight planners to classify nanotechnology research according to the point at which they contribute to products development and commercialisation. Basic research contributes more to the nano-materials, while applied research contributes more to nano-intermediates. The nano-intermediates are semi-finished products with nanoscale features such as sensors and detectors. Innovation and commercialisation are more visible through nano-enabled products. In the nano-enabled product stage, there is hybridisation/incorporation of nano-intermediates into existing industries; for example, there will be solar cells being incorporated into energy products or electronics, resulting in nano-energy and nanoelectronics, respectively.

South African publications were analysed and categorised according to the nanotechnology value chain. Figure 6 shows that before 2013, the majority of papers produced (49%) were in nano-materials; however, as of December 2019, more papers produced are now in the nano-intermediaries stage (52%). The number of papers reporting on nano-enabled products also went up by 1%, from 3% to 4%, and this shows that the nanotechnology research system is evolving and moving towards the more innovative and commercialisation-oriented stages of the value chain.

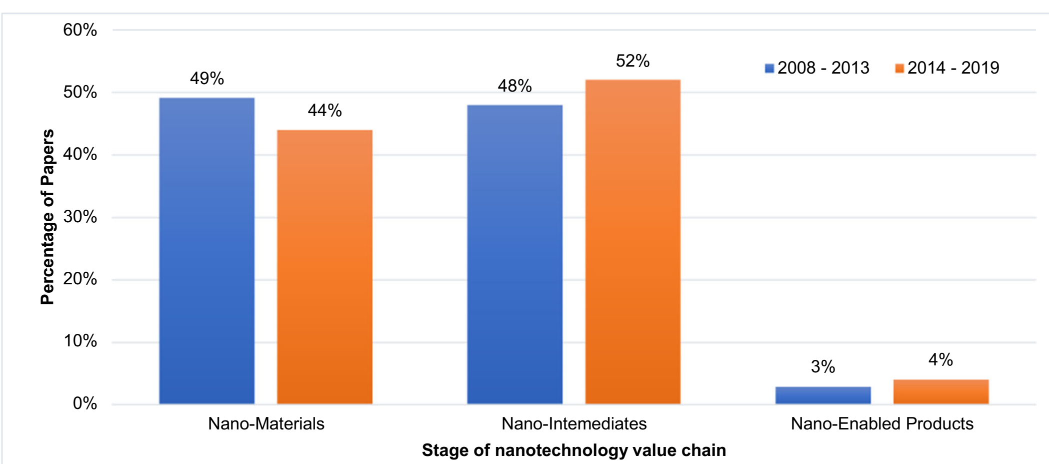

Fig. 6 Publications classified according to the nanotechnology value chain for two periods

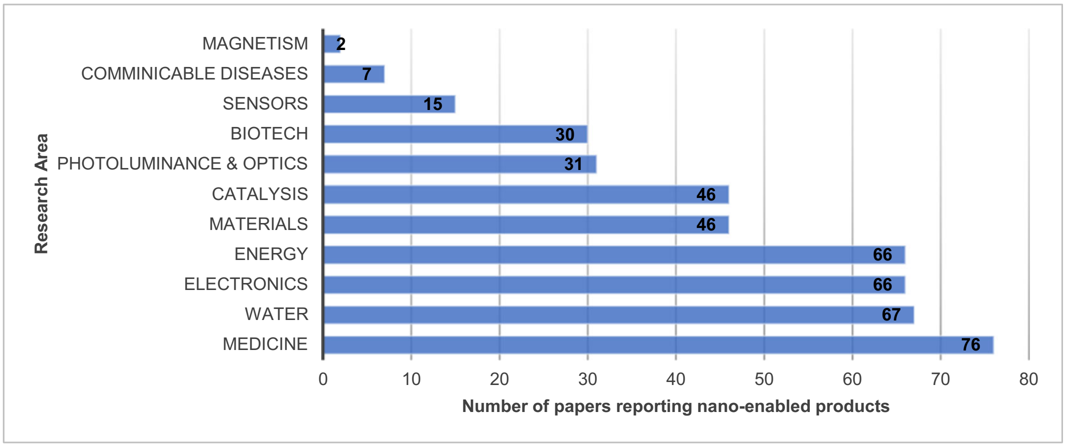

Fig. 7 Number of papers reporting nano-enabled products per research area

The ultimate goal of science and technology is to develop nano-enabled products that can be used to address socio-economic goals and improve the quality of life. Figure 7 below shows the number of publications reporting on nano-enabled products per research area. Medicine has the highest number of papers at 76, followed by water, electronics and energy.

South Africa's selected nano-enabled product papers compared with BRICS countries

South African papers reporting on nano-enabled products were compared with BRICS countries using the last 5000 publications up to December 2019. Figure 8 below shows the comparison of publications in medicine, electronics and energy. South Africa and Russia produced the least publications on nano-enabled products. China has the highest number of publications related to nano-enabled products, followed by India. The results seem to confirm the widely held view that China is the leading producer and exporter of electronics (Gangnes and Van Assche 2008; Investopedia 2019).

Conclusions

In the last 20 years spanning from the year 2000 to 2019, nanotechnology in South Africa has grown exponentially, publications per year increased from 68 in 2000 to 1672 in 2019, an increase of 2458%. Nanotechnology

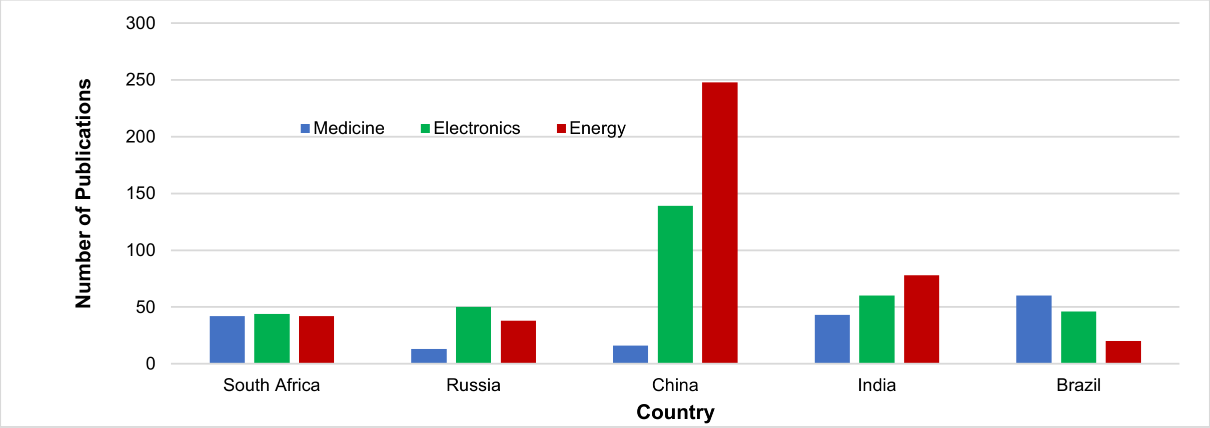

Fig. 8 South Africa publications reporting on nano-enabled products relative to BRICS countries

research also grew at a faster rate as compared with overall publication growth, which experienced 508% growth over the same period. The total share of nanotechnology publications increased from 1.4% in 2000 to 6.6% in 2019, thus an average of 0.52% increase per year. However, when compared with BRICS countries, South Africa has the lowest nanotechnology productivity with an activity index of 0.68 for the last 20 years. China is the most productive with an activity index of 2. This picture is not very different when the recent past year 2019 is considered. From a foresight perspective, South Africa can benefit from collaborating with the more productive BRICS countries, benchmark their strategies and policies to help South Africa improve and achieve comparable nanotechnology activity levels.

The top four publishing subject areas, namely chemistry, material science, physics and engineering, together account for 93.05% in the last 20 years and 95.34% in 2019 of nanotechnology publications for South Africa. When the year 2019 is considered separately, the emergence of computer science as one of the top 20 subjects publishing in nanotechnology suggests a convergence of nanotechnology and computing science, or drive from artificial intelligence (AI) system design and the drive towards the 4th Industrial Revolution (4IR). However, additional investigations need to be done to ascertain the existence and extent of the fusion of nanotechnology, biotechnology, information technology, cognitive sciences and artificial intelligence (NBICA) in South Africa.

Universities are the most prominent publishers of nanotechnology research in South Africa, followed by national research facilities. In the last 20 years, the most prolific publisher among universities is the University of Johannesburg, contributing 14%, while the most prolific national facility was the CSIR contributing 9%. When the 2019 1-year snapshot is considered, the top publishers remained mostly unchanged, with the University of Johannesburg still at the top. However, the University of South Africa, iThembaLABS and Tshwane University of Technology show that they have increased their nanotechnology activity, producing more relative publications. There was minimal participation of the private sector in nanotechnology research, and this will negatively impact the innovation and commercialisation of nanotechnology research. From a foresight perspective, this indicates that there is a need to engage more private sector to be involved in nanotechnology research through programmes such as joint research with academic institutions.

The publication output is heavily skewed to the most prolific authors such that the top ten authors jointly contributed 21.35% in the last 20 years, and in 2019 alone, the top 10 authors contributed 20.39% of publications. This result is inline with Lotka's law (Phillips 2013) which state that the distributions of science and technology publications are highly skewed such that the leaders tend to be extremely prolific, while the rest occur in "ones and twos." When the year 2019 is considered separately, there is the emergence of new top authors that suggested that new researchers/authors are coming into the system mixed with experienced authors who have been there for years. This mixture is essential in foresight planning because it demonstrates continuity, and it suggests some form of succession planning taking place within the nanotechnology system of South Africa.

International and local collaborations are important for science and technology development. Internationally, India is the largest collaborating partner for South Africa, co-authoring 11% of publications, while in Africa, Nigeria is the most significant collaborator. The relative percentage of co-authored papers between South Africa and the BRICS countries increased in 2019 compared with the last 20 years; for example, in 2019, Russia now appears on the top 20 collaborating countries at number 17, but it did not appear on the top 20 list for the last 20 years; this can be attributed to efforts made under the BRICS collaboration. There is a high degree of collaboration between researchers varying from 0.95 to 0.99, and 3 or 4 authors write the majority of papers. However, there is a lower degree of collaboration among organisations varying between 0.69 to 0.78, and the majority of papers are authored by researchers from a one or two institutions.

The strategic nanotech research areas with a socioeconomic benefit for South Africa were identified to include materials science, photoluminance and optics, medicine, catalysis, electronics, energy, biotech, magnetism, sensors, water and communicable diseases. The top publishers per research area were identified; for example, in material science, it is Ray Suprakas, in medicine it is Nyokong Tebello, in electronics and energy it is Maaza Malik, in water it is Mamba Bhekie, in photoluminance and optics it is Swart Hendrik. Top publishing institutions per research area were also identified; for example, in nanomedicine, it is the University of KwaZulu Natal, University of Witwatersrand and University of Cape Town. University of the Free state is the leading publisher in photoluminance and optics, and the University of Pretoria is the leading institution for nanoelectronics. India is the top collaborating country in seven research areas; however, for medicine and communicable diseases, the top collaborating country is the USA, for energy China, and for water Belgium.

Nanotechnology companies tend to cluster into some regions instead of being evenly distributed in a country; hence, regional clusters for the different research areas were also examined using the country's economic hubs. The results indicate that provinces are strong in different sub-fields of nanotechnology. For example, if one needs to develop a business in photoluminance and optics, they need to locate either in Pretoria or the Free State, for nanomedicine, they need to be in Western Cape or Johannesburg, and communicable diseases research in Western Cape or KwaZulu Natal region.

The quality of papers was evaluated using citation rates, electronics has the lowest citation rate at 13.3 citations per paper, and communicable diseases have the highest citation rate of 33.8 citations per paper. The level of innovation for the research areas was evaluated using the nanotechnology value chain, and medicine has the highest number of papers reporting on nano-enabled products followed by water, electronics and energy. When South Africa is compared with the BRICS countries using the last 5000 publications of 2019, China has the highest number of publications related to nano-enabled products, followed by India. The results seem to confirm the widely held view that China is the leading producer and exporter of electronics (Gangnes and Van Assche 2008; Intrepidsourcing 2018; Investopedia 2019). South Africa needs to benchmark with these other countries to increase its level of innovation and nano-enabled product output.

In conclusion, this research has presented an environmental scan of nanotechnology in South Africa for the past 20 years, and also evaluated possible socio-economic relevant sectors arising from this information. Foresight planners, investors, government policymakers and R&D managers can use the information to evaluate the possible nanotechnology research areas in which they can invest in South Africa.

Limitations of the study

While scientometric indicators present quantitative and evidence-based indicators for foresight studies, they suffer from several limitations. Scientometric indicators are lagging indicators because it takes an article at least a year or more to be published, while patents can take several years to be granted. Tech-mining can answer questions on who, what, where and when. However, the answers to questions regarding the process of how, and the reason why almost always require expert opinion to answer them (Porter and Cunningham 2005). Not all research is published or patented, for example, an academic scientist or engineer is 45 times more likely to publish his/her research than an industrial counterpart (Porter and Cunningham 2005). Scientometric indicators are at best proxies of more 'intangible' dimensions, for example, scientometrics tend to reduce constructs like "research quality" to "citation impact" and "research collaboration" to "co-authorship", these are complex aspects. Thus, current bibliometric methods are simply inadequate to measure such properties adequately and need to be augmented by other evaluation methods.

Recommendations

As an emerging research area, the system of classifying nanotechnology papers into economic sectors such as nanomedicine, nanoenergy, nanoagriculture, nanoelectronics and so on is not yet well established. Secondly, most researchers do not file patents; hence, it is sometimes difficult to evaluate the state of innovation using patents data because the data will be little. For example, between 2000 and 2019, South Africa produced only 43 patents on the European Patents Office (EPO) database versus a massive 11,625 publications on WoS core collection. Hence, one way to evaluate innovation will be to use the nanotechnology value chain classification of papers. Unfortunately, the system for classifying publications according to the nanotechnology value chain is also not well developed. Thus, there is a need to develop further and refine nanotechnology research area systems classification systems that can be used to evaluate research areas for foresight and research portfolio management purposes.

When the year 2019 is considered, the emergence of computer science as one of the top 20 subjects publishing in nanotechnology suggests that nanotechnology convergence (Roco 2020) is happening the country. In addition, it was observed that there is a high degree of author/researcher collaboration within nanoscience in South Africa; this may also suggest convergence of disciplines with nanoscience research, but we are not sure at this stage, one needs to investigate if these authors are collaborating across disciplines or within disciplines. Hence, additional investigations need to be done to ascertain the existence and the extent of the fusion of nanotechnology, biotechnology, information technology, cognitive sciences and artificial intelligence (NBICA) within the South African nanoscience landscape. There is also a need to investigate and understand if convergence is in the confluence phase, for example, just across disciplines and subjects, or it has advanced to the integration phase where frameworks and systems are now developed to solve problems that individual capabilities/disciplines cannot solve on their own (Roco 2020). Such an investigation will enable foresight planners to understand how nanotechnology convergence is evolving and how the future may look for the country's national innovation system.

Acknowledgements Vantage Point Student Edition Technology Mining Software.

Declarations

Financial interest Author Brian Masara received Doctor of Business Leadership (DBL) bursary funding from the University of South Africa (UNISA) for this research.

Conflict of interest The authors declare that they have no conflict of interest.

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