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Contribution of Nanotechnology for Sustainable Development in African: Opportunities and Challenges

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Abstract

Nanotechnology is one of the fast-growing technologies through advanced research from fundamental to experimental science for numerous applications in different fields, including defense, aeronautics, electronics, communication, agriculture, livestock, medicine, textile and food sectors. Many advanced countries such as USA, China, India, Iran, UK, Germany, Japan and many others have in the last two (02) decades ago, launched and developed many nanotechnology initiatives and programs for their socio-economic development. In line with their development strategies, several countries in Africa have also launched their nanotechnology initiatives and programs. Unfortunately, most of them are still at the stage of demonstrating interest and understanding its implementation. Despite the indicators show a broad impact on nearly all industrial sectors of the global economy and sustainable development, there are various challenges related to the development of nanotechnology in the African continent. Over the past five years, the global statistics reveal that the total nanopublications in Africa is equal to 2.4 times lower than that of China in the single year of 2022, while the number of patents applied by South Korea in one (01) year period is seven (07) times the total patents applications of the two leading countries (South Africa and Egypt). This lower growth rate is related to the unclear nanotechnology programs, critical lack of of strong industry and inability to translate R&D investments to economic outcome, lack of human and policy capacity and the absence of appropriate academic and research infrastructure. Other barriers are associated with non-implementation of intellectual properties rights and lack of proper collaborations and partnerships. This work aims to assesses the current status of nanotechnology in Africa for a sustainable development while integrating opportunities and challenges. The methodologies used in this work were based on web of science (WoS) database including StatNano database and the combination of lexical query and journal search. The results indicate a poor nano production at the continental level compared to the rest of the world.

Keywords: Africa; Nanotechnology; Initiatives; Socioeconomic development; Challenges; Opportunities

Introduction

Nanoscience and nanotechnology offer new opportunities for promoting sustainable development. In light of nanotechnology's potential to cope with global challenges, such as energy production for a growing world population, it is seen as a great contributor to sustainability. In a short time, nanotechnology has significantly impacted several socio-economic sectors, including semiconductor manufacturing, energy production, medicine and agriculture [1]. Therefore, nanotechnology appeared as a technology platform that improves products and processes [2]. In the past century, mayny technological innovations and the development of hybrid varieties helped crop production [3, 4]. Furthermore, the advent of biotechnology has significantly increased the production of crops that resist various biotic and abiotic factors such as viruses, pests, drought, salinity, etc. [5]. In their investigations, Savolainen et al., (2010) [6] and Brinker et al., 2020 [7] found that thermal energy storage can be better developed by using nano-porous materials such as zeolites in heat storage systems in both residential and industrial areas [6-8]. Tan et al., 2012 [9] examined the advantages of using carbon nanotubes in solar energy conversion and storage, lithium-ion batteries, hydrogen storage, electrochemical supercapacitors and green nanocomposite designs. They conclude that carbon nanotubes are likely to increase energy conversion efficiency and be countable for the future of renewable energy. Savolainen et al., (2010) [6] found that the performance of batteries and supercapacitors can be significantly improved with nanotechnology. Kumaş et al., (2020) [10] have shown that solar cells made of nanocrystals have efficient structures. Thanks to their flexibility, thin film solar cells-based nanomaterials find wide usage in buildings compared to conventional glass panel solar energy systems based on silicon. In addition, they can eliminate the aesthetic problems caused by traditional [11-15]. Medicine is one in which nanotechnology is playing an important role. Several studies have demonstrated the utilization of nanoparticles (NPs) as potential drug delivery systems. Anna et al., (2015) [16] have shown that nanoparticle Abraxane, an albumin-bound paclitaxel, is used for the treatment of breast and cell lung cancer (NSCLC) [16, 17]. In their report, Weissleder et al. (1990) [18, 19] demonstrated that iron oxide NPs are usable for liver cancer detection. The nanoparticles and nanomaterial-based imaging agents, such as quantum dots (QDs), can be used in conjunction with magnetic resonance imaging to produce images of tumour sites [16, 18-21]. Other examples include supercomputers, cell phones and video game brands, in which lithium batteries with nanocoated anode and nanoelectromechanical devices play a role. These few highlights demonstrate the potential of nanotechnology in general for addressing problems. From the synthesis to the applications and commercialization, nanotechnology bears significant benefits for the entire society. Thus, nanotechnology is captivating investments from the private sector and governments in most developed countries [22, 23], as well as developing countries. As the 21st revolutionary technology in diverse fields, nanotechnology emerged as an indispensable asset in the modern world. Many advanced countries such as the USA, China, Russia, Japan, the UK, Germany, Korea, and others have since two (02) decades ago developed robust nanotechnology programs and initiatives for consistent investment in their respective countries. Adiguzel et al., (2020) [24], have indicated that the investment in nanoscience and nanotechnology worldwide is approximately a 1/4 of a trillion US$, with a proportion of investment reaching more than 2 billion US$ for the US and China. Theresa et al., (2022) [25] reported that these two dominant economies ranked as nanotechnology giants and leaders in the volume of nanotechnology government investment. For the past two decades, a few African countries, such as South Africa and Egypt, have launched their nanotechnology program. The majority has only demonstrated interest in starting without any practical approach to its implementation. Here, we highlight a few examples of initiatives and programs in nanotechnology of the two giants in Africa's nanotechnology development. Since 2002, South Africa has launched several nanotechnology programs and initiatives that include the National Nanoscience Teaching and

Training Platform (NNPTTP) and two national nanotechnology innovation centres (NICs), the National Centre for Nano-Structured Materials (NCNSM) and the DST/Mintek NIC, focusing on materials and energy research, health research, sensors, and water research and development. The need for trained personnel in the field of nanoscience has led to the establishment of the National Nanoscience Postgraduate Teaching and Training Platform (NNPTTP). The second giant country (Egypt) also initiated the Egypt Nanotechnology Centre (EGNC) to support its industrial research sector. The main areas of this centre include Computational Modelling and Simulation, Thin-Film Silicon Photovoltaics, Spin-On Carbon-Based Electrodes for Thin Film Photovoltaics, Nano-Biotechnology and Energy. For instance, nanotechnology products are still at laboratory scales and have not yet significantly impacted lives within the continent. However, several works reported in the literature have indicated the potential of nanotechnology in improving the lives in Africa. Considering the status of nanotechnology in the world, particularly in Africa, the areas where nanotechnology can generate the most benefits for society can be grouped into social and industrial development clusters. For the social cluster, the benefits of nanotechnology have contributed to primary health care. The South African scientist community from the biotechnology-based company Afrigen Biologics has successfully produced a lab-scale batch of a COVID-19 vaccine that is similar to that made by pharmaceutical company Moderna reported in [26]. In the field of agriculture, Rineke et al., 2024 [27] have demonstrated the benefits of Nanofertilizers for Food Security in sub-Saharan Africa. They indicated that Nanofertilizers are capable of effectively delivering nutrients, which reduces the amount of fertilizer required and minimizes environmental impacts such as leaching into soil and water. From the industrial point of view, Adewale et al., 2024 [28] has indicated that Egypt is particularly keen on developing nanotechnology products for hydrocarbon operations in its oil and gas industry.

The present work aims to review the current state of nanotechnology progress and the evidence of opportunities for its development within the African continent.

Materials and Methods

Data for the analysis presented in the article were sourced from the Web of Science (WoS) database [29], a preferred database widely used for mapping science and scientific development in countries. Statistics from the database were gathered individually for more than 20 developed and developing countries worldwide, including a dozen countries on the African continent, before sorting them according to the number of research publications as classified in the database. The complementary method was the combination of glossary query and journal search. We focused on peer-reviewed articles published in English due to difficulties with language translation. The exploited databases include Scopus, ScienceDirect, Chemical Abstract Service (CASSI) and Medline. This method was first introduced by Porter et al., (2007) [30] with a large number of nano-related keywords. Gorjiara et al., (2014) [31] have used this method to compare the nanoscience and nanotechnology output between Australia and the rest of the world. Several nano-terms were excluded [32]. Hsinchun et al., (2013) [1] have also used a keyword search approach to identify scientific publications and patent data from the WoS and USPTO databases. The evaluation of the number of publications and the growth rate for a selected country in a defined year was calculated using the following expression [33].

$$\mathrm{RGR} = \frac{\ln \mathrm{N}_2 - \ln \mathrm{N}_1}{\mathrm{t}_2 - \mathrm{t}_1} (1)$$

where Ni represents the number of publications in a defined year and ti corresponds to the considered year. The calculation is often adjusted as a coefficient in case the total publication in a given year is not defined. In this study the rapid growth rate was calculated basing on the last five years (2017-2022).

The limitations: Similar to other scientometric analysis, there are some potential limitations in the current investigation. The study is limited for five years period. The methodology is mainly focused on the use of WoS functions for the analysis. Another potential limitation is in evaluating the papers published in a country by extrapolation. This approximation can lead to an overvaluation or undervaluation of published papers and patent applications and consequently, can affect the quantity of articles available for a chosen country. Therefore, the data reported here and in databases must be considered with a reasonable margin.

Results and Discussion

Statistical Assessment of Current Scientific Research Production

Nanotechnology contributes to every field of science. In this case, the production of articles in nanotechnology is indissociable from that of the global sciences. Evaluation of global science production aimed to respond to a statistical point of view of African countries' contribution. Figure 1a shows the contribution of the ten most prolific countries (China, the US, the UK, India, Japan, Germany, Italy, Canada, France and Australia). The results indicate that from 2017 to 2022, the worldwide highest production obtained in 2021 was approximately 2.8 million articles. In 2022, the number of publications has dropped to 2.5 million. This observation may find an explanation related to COVID-19 and the current war, which affects the international collaboration between scientists. The sharing calculations show that approximately 82% of scientific productions are from the mentioned advanced countries. The results indicate that global research is topped by the two largest economies, China with 23.23% and US with 22%, of worldwide production. 6% for UK and 5% for Germany. Compared to the rest of the top scientific contributors, only China presents a remarkable growth rate (Figure 1b).

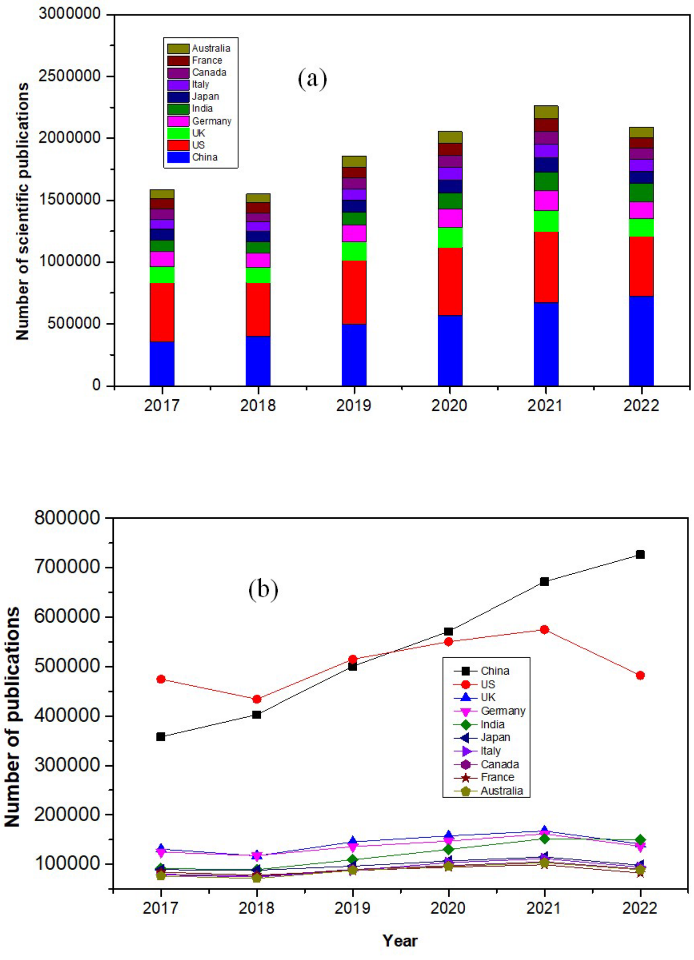


Figure 1: a) Distribution of scientific publications of the top 10 contributors worldwide b) evolution of publications in 5 year period from 2017 to 2022

From the evaluation in terms of scientific production, the indicators show that research publications in Africa have increased substantially. Figure. 2a depicts the 10 top productive countries' achievements within the last five years. The 2 top ranked are Egypt with 145214 and South Africa with peer-reviewed articles, (Fig 2a). However, one can observe a decline in the number of publications in South Africa from 2021 (see Figure 2b) because the number of publications for Social Sciences and Engineering and Technology has declined according to the 2022 South African Science, Technology and Innovation Indicators Report [34], the proportion in Engineering and Technology has decreased from 28,2% in 2019 to 22,2% in 2020, while Social Sciences publications decreased from a share of 30,2% in 2019 to 27,5% in 2020. As a result, this has affected the sharing of total publications in South Africa. Other countries such as Nigeria with 41724 articles held the third rank and is followed by Algeria with 38444 articles. Compared with the 10 top worldwide contributors in science, the total African production remains lower. In their investigation, Sooryamoorthy et al., 2021 [35] revealed that the rapide growth rate of articles in advanced countries is 2 to 20 times that of African countries. They also explained this low contribution using indicators such as Gross Domestic Product (GDP), the percentage allocated to R&D called GERD. Other factors are due to political instability and corruption.

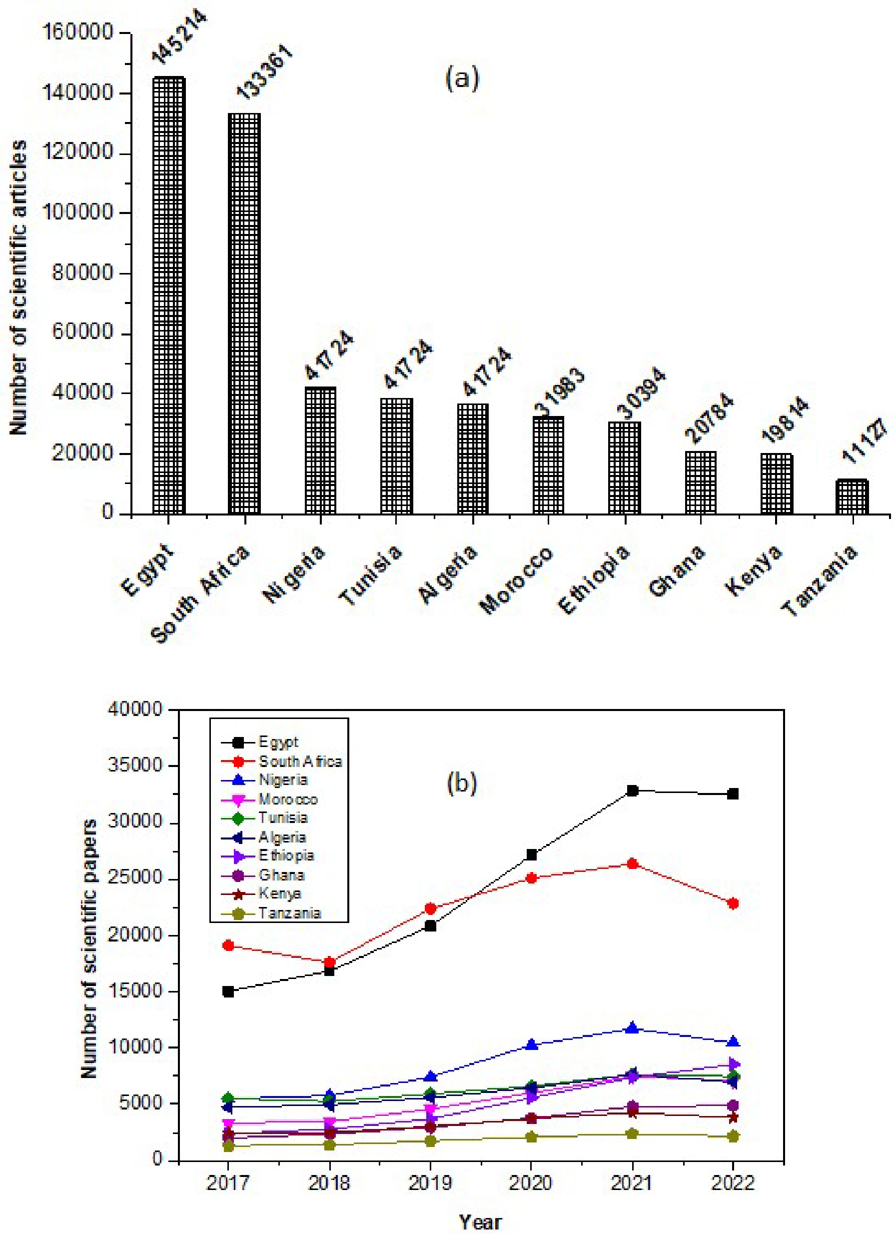
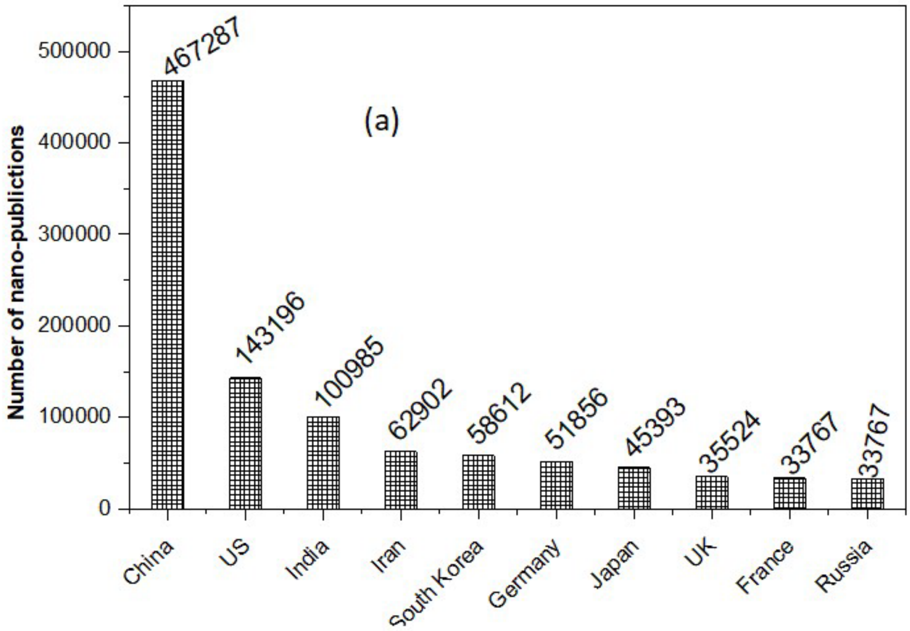


Figure 2: a) Distribution of scientific publications of the top 10 continental contributors; b) evolution of publications in 5year period from 2017 to 2022

Evidence of Low African Contribution in Global Nanoscience and Nanotechnology Production

In the 1990s, few countries counted nanotechnology as a technological revolution that helped problem-solving. Two decades later, the number of initiatives in nanotechnology has exponentially grown worldwide due to the advantages of nanotechnology applications in various fields [35]. During the last five years, the top 10 countries producing the most nanotechnology-related scientific articles were determined by the available WoS and Statnano databases [26] (Figure 3a). The leading prolific contributors are China, the USA, India, Iran, Germany, South Korea, Japan, the UK, France and Russia. Of these countries, China is identified as the country with remarkable nanoscience and technology publications growth, as shown in the annual production evolution in Figure 3b. The number of articles related to nanotechnology indexed in WoS by China was equal to the combined nanotechnology-related publications of the nine countries, with 106586 articles at the end of 2022. This achievement finds its explanation through the numerous academic institutions, research centres, the abundant workforce and the great attention to nanotechnology given by China. The US has secured second place, while India, Iran, and South Korea hold the third, fourth and fifth positions, respectively. Only Egypt in Africa is ranked when appearing in the 25 top countries nano-contributors.



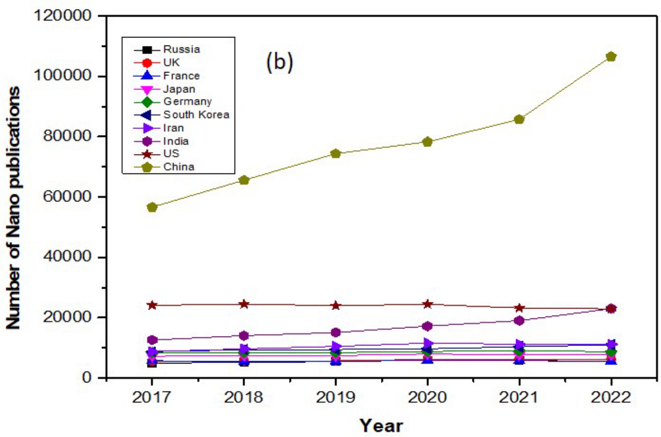


Figure 3: a) Distribution of nanotechnology publications of the top 10 world's contributors; b) evolution of nanopublications in 5 year period from 2017 to 2022

Nanotechnology Initiatives in Africa

Since 2002, several developing countries have launched their nanotechnology initiatives and programs [22], while advanced countries are developing competition in nanotechnology products and their commercialization. Because of the prominent results, nanotechnology has been declared a strategic sector of scientific and technological development [36] in some African countries. Therefore, countries like South Africa, Sudan, Kenya, Zimbabwe, Egypt, Algeria, Morocco, Tunisia and Nigeria have made great strides in harnessing nanotech applications in various socio-economic areas, based on the last 20 years nanotechnology initiatives [37][38] as presented in Figure 4. The data analysis showed that South Africa is ranked first with a total of nine (09) initiatives, followed by Nigeria with four (04) initiatives. The remaining countries presented a number comprised between one (1) and two (2) initiatives.

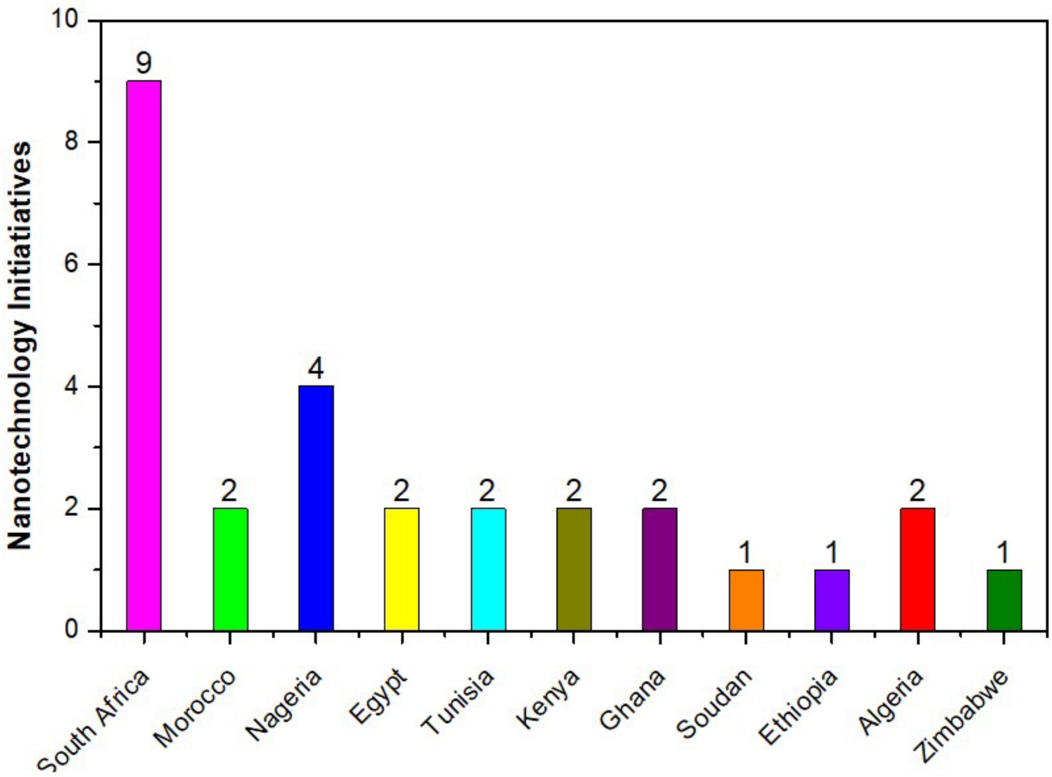
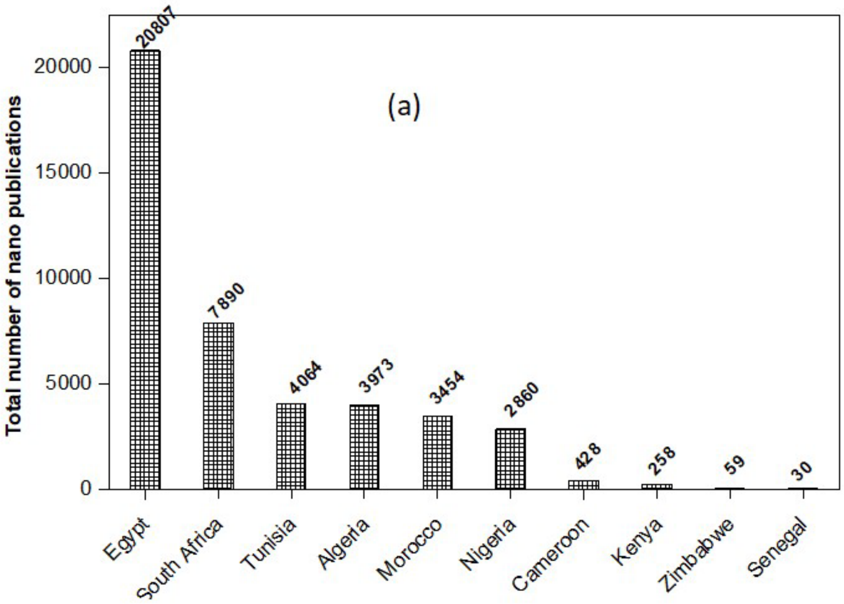


Figure 4: Distributions of nanotechnology initiatives in Africa

Figure 5a shows the annual distributions of nanopublications by the most prolific countries. Egypt is ranked first in nanotechnology research with a contribution of 47.48%, followed by South Africa with 18%. The third rank goes to Tunisia with 11%. From a sub-Saharan point of view, South Africa ranked first, followed by Nigeria, with a contribution of 6.53%. Cameroon (0.98%), Kenya (0.59%), Zimbabwe (0.13%) and Senegal (0,07%) of contribution. The curve shown in Figure 5b indicates that Egypt has an increasing growth while the number of nanopublications in South Africa decreases from 2020 to 2022. These results show the low contribution of Sub-Saharan African countries in nanoscience and nanotechnology. The global assessment related to R&D in nanotechnology from 2000 to present revealed that South Africa has the highest ranking (66%) in R&D related to nanotechnology, followed by Egypt (59%) and Nigeria (38%) [39, 40].

Nanotechnology Inventions at the African Continental Level

The trends in patent applications may indicate the perceived value of the knowledge and products generated in technological and economic terms. By looking at patents filed with the two leading patent offices, the United States Patent and Trademark Office (USPTO) and the European Patent Organization (EPO), it is possible to evaluate the differences in patenting practices in Africa. Figure 6 depicts the total number of patent applications over the last 5-year period. At the continental level, Egypt and South Africa lead in patent applications filed with USPTO and EPO offices. From 2017 to 2022, South Africa counted 34 patent applications in nanotechnology-related inventions, while Egypt presented 18 patented applications. South Africa has also established the most nanotechnology companies and institutions. Although patent applications are increasing, the number of nanopublications remains low. Indeed, South Korea applied for more nanotechnology patents with the USPTO in 2021 than the total number of nanotechnology patent applications in the African continent over the last 22 years. Less than 1/10 of African countries have developed clear national nanotechnology strategies to guide the sector development and the economy. As a result, Africa is lagging in nanotechnology research and inventions.



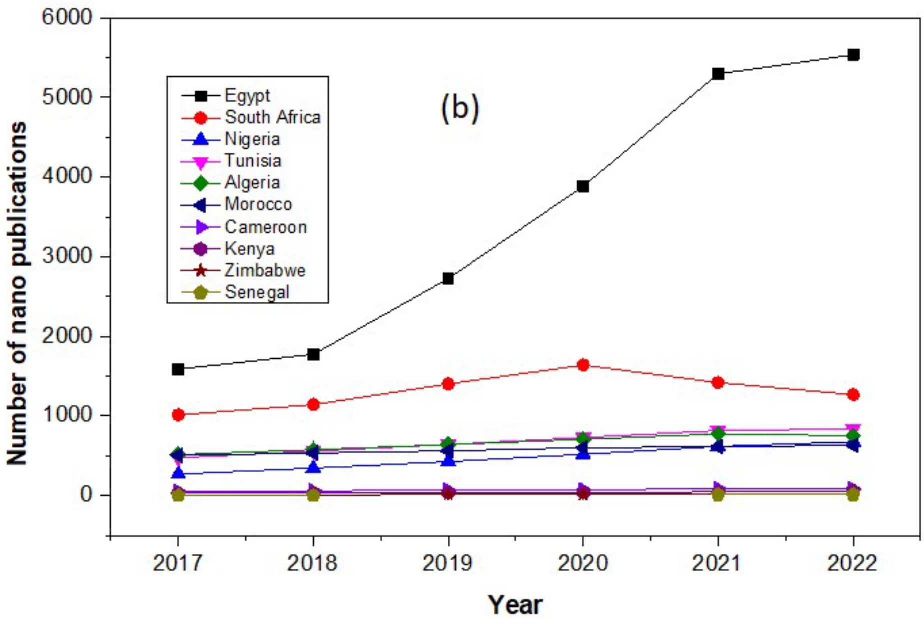


Figure 5: a) Annual distributions of nanopublications by the most prolific countries in Africa;
b) evolution of nanopublications in 5 year period from 2017 to 2022

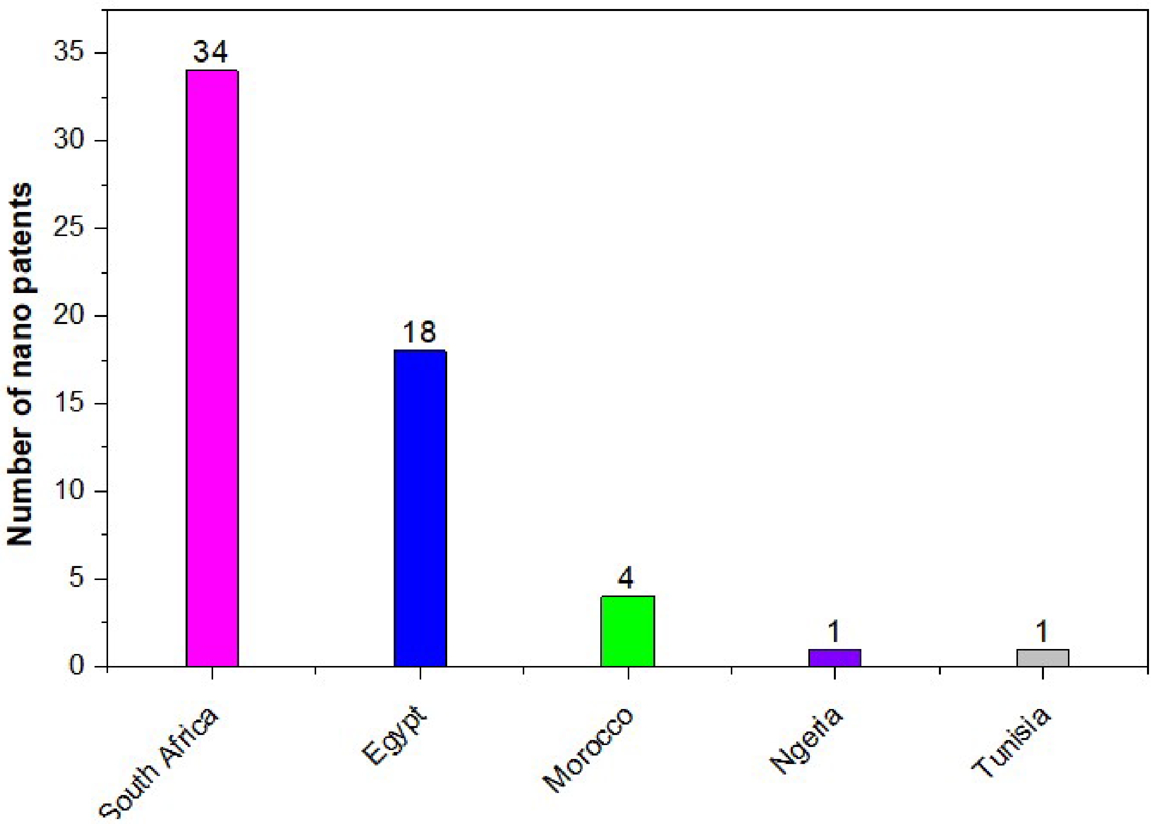


Figure 6: Distribution of patent applications across the African from 2017 to 2022

Nanotechnology as an Opportunity for Sustainable Development

Nanotechnology Global Market

In 2015, the Nanomaterials market was esteemed at USD 4,097.17 million with a compound annual growth rate (CAGR) of more than 22% [24]. Nanda et al., 2020 [41], the booming global nanotechnology market is projected to exceed US$ 125 billion by 2024. The rapid growth of the nanotechnology market is driven not only by increasing investment in research and development but also by the significant potential for benefit to society through their various innovative and industrial domains that include aerospace, defense, transportation, materials, energy, electronics, medicine, agriculture and environmental science, and consumer and household products [42], as presented in Figure 7. We also observe a remarkable usage of nanoproducts such as silicon dioxide and silver in medicine, cosmetics, construction and automotive. Therefore, there is a motivation for investing in nanotechnology. This investment worldwide reaches approximately a quarter of a trillion USD, with China and the USA injecting upwards of US$ 2 billion [24]. Of these two nanotechnology giants, China dominates in the nano-article contributions, while the USA leads in the volume of nanotechnology industrial products and government investment [23, 24, 43, 44]. Companies which are more focused on manufacturing nanotechnology-based products and their headquarters are listed in Table 1 [25]. Although the nanotechnology market in Africa does not show the same strength, countries like Egypt, Tunisia and South Africa are making steady investments [39]. Therefore, the number of companies interested in nanotechnology markets is also expanding. However, most of these companies, including African Pegmatite, Comar Chemicals, Council for Scientific and Industrial Research (CSIR), Denel Dynamics, Mintek and SabiNano, are based in South Africa.

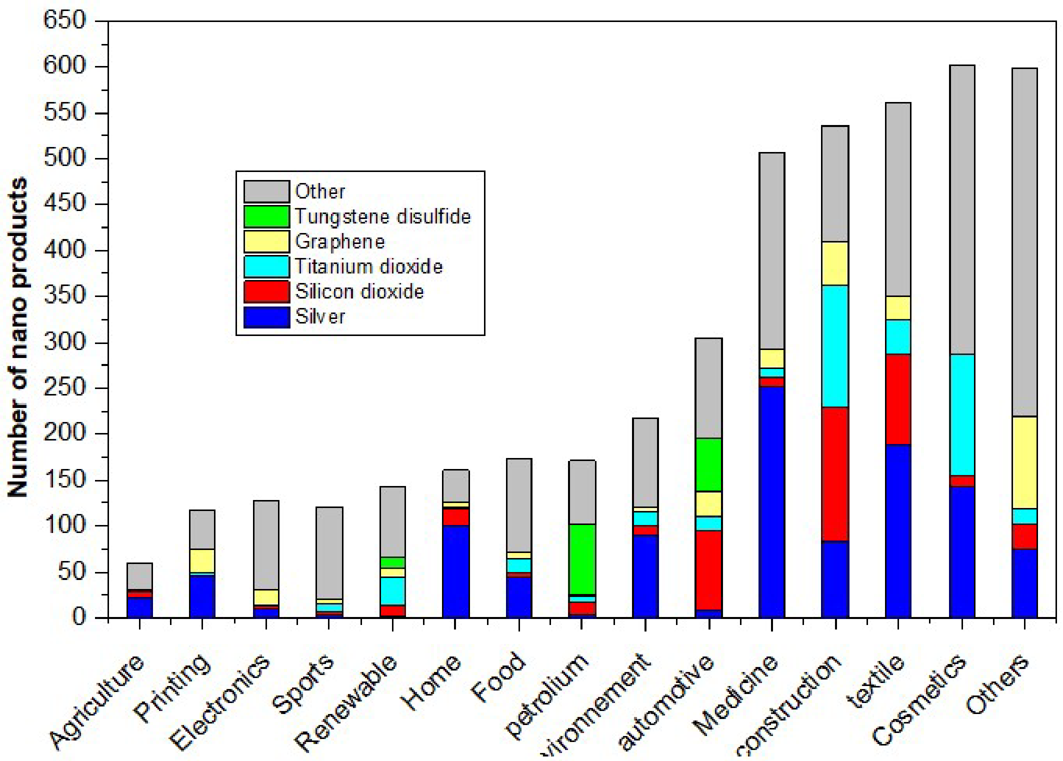


Figure 7: Nanotechnology industrial products in various domains

Country	Company	Operation
USA	3M	Manufactures numerous nanomaterials
	BNNano, Inc.	Manufactures boron nitride nanotubes (NanoBarbs™)
	Cerion	Manufactures metal, metal oxide, and ceramic nanomaterials
	Rezenerate NanoFacial	Develops nanofacials using innovative devices for cosmetics delivery
India	Log9 Materials	operating in the areas of sustainable energy and filtration.
UK	Advanced Material Development	Develops 2D nanotechnologies and metamaterial systems
	Applied Graphene	Develops and applies graphene
France	Nanomakers	Develops and commercializes nanoparticles of silicon carbide
	Superbranche	Develops functionalized metallic oxide nanoparticles
Germany	RAS AG	Produces and distributes nanomaterials
Japan	Zeon Corporation	Manufactures single-walled carbon nanotube
Luxembourg	OCSiAl Luxembourg	Produces graphene nanotubes
Portugal	INNOVNANO	Manufactures ultra-fine nanostructured ceramic powders
Canada	CelluForce	Produces a form of cellulose nanocrystals (CelluForce NCC™)
Spain	Nanogap	Manufactures novel nanomaterials from atomic quantum clusters

Table 1: Global nanotechnology industry

Typical Opportunities for Africa

Nanotechnology presents significant opportunities for advancing economic, social and environmental development aspirations in developing countries. As an enabling factor, nanotechnology could play an important role and impact the Goals for which technology supply and demand are high. Given that African countries are at various stages of socioeconomic development, the potential impact of nanotechnology is more likely to vary from one country to another. However, nanotechnology can directly be applied to the Sustainable Development Goals 2, 3 and 7 due to the significant business opportunities related to these Goals. Moreover, the areas associated with these goals are susceptible to financial opportunities for consistent investment. The typical top 10 domains for nanotechnology applications and the associated Sustainable Development Goals are highlighted in Table 2 [45].

No	Area	Primary goal	Secondary goal
1	Energy storage, production, and conversion	7 (Energy)	9 (Infrastructure, industrialization)
2	Agricultural productivity enhancement	2 (Zero hunger)	1 (End poverty in all its forms)
3	Water treatment and remediation	6 (Water and sanitation)	3 (Health)
4	Disease diagnosis and screening	3 (Health)	9 (Infrastructure, industrialization)
5	Drug delivery systems	3 (Health)	9 (Infrastructure, industrialization)
6	Food processing and storage	2 (Zero hunger)	13 (Climate change)
7	Air pollution and remediation	11 (Cities)	3 (Health)
8	Construction	9 (Infrastructure, industrialization)	11 (Cities)
9	Health monitoring	3 (Health)	11 (Cities)
10	Vector and pest detection and control	3 (Health)	11 (Cities)

Table 2: Top 10 domains for nanotechnology applications and the associated Sustainable Development Goals

African Natural Resources for Nanotechnology Development

As indicated in section 3.4.2, nanotechnology is becoming increasingly aware of unmet needs across the continent through the area associated with the Sustainable Development Goals. Most of the nanocomposites and nanomaterials used in these domains are inorganic nanoparticles and mineral-based. These nanomaterials include calcium, magnesium, silicon dioxide, titanium dioxide and silver nanoparticles [46] [47] [48][49] for which the raw materials are available across the continent. In a report, the United Nations [50] indicated that Africa possesses about 30% of the mineral reserves worldwide while holding around 40% of gold and up to 90% of chromium and platinum. Table 3 presents the global distribution of natural minerals in the top 10 countries. The production of nanomaterials from these raw materials would place the continent at the level of nanotechnology player on the world stage.

Country	Minerals
South Africa	Gold,, platinum, chrome ore, manganese ore, zirconium, vanadium, titanium.
DRC	Lithium, cobalt, tantalum, diamonds, gypsum, gold, copper, cobalt, tin, tantalum

Ghana	Gold, diamonds, manganese bauxite, iron ore, copper, chrome, nickel, limestone, quartz and mica
Mali	Gold, iron ore, uranium, manganese, lithium, and limestone
Burkina Faso	Gold, zinc copper, manganese, phosphate, lithium, diamond, and limestone
Kenya	gold, iron ore, talc, soda ash, some rare earth minerals, and gemstones, limestone, niobium, iron ore, gemstones, and salt.
Nigeria	Wolframite, tantalite, bitumen, iron ore and uranium
Rwanda	Tantalum, tin, tungsten, gold, gemstones. diatomite, limestone, talcum, gypsum, and pozzolan
Botswana	Gold, iron, titanium, zinc copper, nickel
Egypt	Gold, copper, silver, zinc, platinum
Zambia	Bobalt, nickel, manganese. Copper
Guinea Conakry	Bauxite, iron ore, gold, diamond

Table 3: Top 10 mineral countries in Africa

Challenges in the Nanotechnology Implementation in Africa

Several African countries have expressed an interest in nanotechnology but failed to undertake long-term projects that could impact the community's lives. Most research on nanotechnology is of only academic interest and of limited relevance to the challenges. Alongside political instability, the challenges are of infrastructural and financial order. Consequently, institutions and research centres remain without adequate equipment for research and innovation in general and nanotechnology specifically. As a fast-emerging technological field and unlike other technologies whose applications are specific, nanotechnology cuts across many manufacturing sectors? For that, its direct contribution is difficult to evaluate. Despite the benefits and growing interest in nanoparticles, numerous uncertainties and risks associated with their use in human health and environmental aspects remain problematic. From the production of articles and patent applications point of view, the indicators revealed that the nanotechnology research base and production in Africa are either small for assessment or quasi-inexistent. The challenges related to the development and implementation of nanotechnology also include the lack of proper legislation framework and relevant political drive. Given the multi-disciplinary nature of nanotechnology, one common challenge is the development of standard curriculum features, with the effectiveness of integrating nanotechnology concepts into existing coursework [51, 52].

Conclusion

Nanotechnology is at the top of the wave of discovery and innovation while demonstrating a range of applications in diverse fields, including energy, medicine, electronics, agriculture, cosmetics, automotive and others. The five-year longitudinal evolution of nanoscience and nanotechnology in USPTO patent applications and WoS scientific publications reveals continuous growth and fast topical changes. The data analysis showed exponential evolution in the number of patent applications in advanced countries during the last five years. As the two leading countries, the US and China achieve scientific production with more than 1/4 of the worldwide. Since 2002, many African countries have also embarked on nanotechnology initiatives and programs for their socio-economic development. Unfortunately, most of African countries, are still at the stage of demonstrating interest and understanding. Challenges are not only associated with the lack of proper infrastructures but also a good political drive in the field. Consequently, the total nano productions for 5 years period was 2.3 times lower that that produced by China in 1 year period, although the continent is home to about 30% world’s minerals reserves, minerals used in nanomaterials and nano-fabrics. Nonetheless, South Africa and Egypt with clear nanotechnology programs and vision are making good progress.

Overall, the global scientific, nano publications and patent applications are far from satisfactory, while Africa having opportunities to becoming a major player in nanotechnology development on the world stage. African Governments are therefore encouraged to invest consistently in the sector, an alternative solution to the socio-economic development problems.

Declaration of Competing Interest

The authors declare that they do not have known competing financial interests.

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