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Evolution of nanotechnology policy initiatives in the BRICS countries: a comparative overview

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ABSTRACT

The article provides a comparative review of the national nanotechnology initiatives in the largest emerging economies (Brazil, Russia, India, China, and South Africa - BRICS). It focuses on the influential role of state action, the evolution of the initiatives, institutional aspects, and a brief comparison of recent scientific production among the countries. Understanding the context of each country's nanotechnology STI policy is essential for comprehending the scope and the primary challenges faced in developing these programs and initiatives. The methodology involved rigorous bibliographical and documentary research, analysis of scientific production indicators, and the estimation of a nanotechnology Activity Index. The political and institutional complexity and socioeconomic adversities in emerging countries are challenging obstacles to promoting emerging technologies. Government perspectives and their role as technology inducers or fosterers significantly differ among countries, even when they are institutionally similar. Overall, the main nanotechnology initiatives in the BRICS countries have historically been led by the state, resulting in significant scientific advancements but limitations on the potential for innovation outcomes. Alongside institutional heterogeneity in the formulation and implementation strategies, geopolitics plays a crucial role in the initiatives' trajectory, especially in countries vying for international leadership against Western powers.

Keywords: nanotechnology, BRICS, innovation, public policy, STI policy.

Article originality and practical implications: This article offers a original comparative analysis of BRICS nanotechnology initiatives, highlighting state-led advancements and inherent challenges, thereby providing insights for policymakers to enhance innovation strategies in emerging economies.

INTRODUCTION

This article provides a comparative review of the development of national nanotechnology initiatives in the most significant emerging economies (Brazil, Russia, India, China, and South Africa – BRICS). The focus is on the science, technology, and innovation (STI) strategy, emphasizing the role of state action, the evolution of the initiatives, their main institutional aspects, and a brief comparison of recent scientific production among the countries. Reviewing each country's nanotechnology STI policy helps us understand the scope and primary challenges faced in the various areas where the programs and initiatives were developed. In this sense, emerging countries' political-institutional complexity and socio-economic adversities often present obstacles to initiatives in emerging technologies such as nanotechnology. In turn, governments' responses to these situations or assumptions about their role as inducers/fosterers of technology are diverse, even among countries with some institutional similarities.

The potential of nanotechnology as an emerging technology has been projected for several decades. Its incorporation into the STI policy agendas of various countries increased significantly at the beginning of the 2000s (Invernizzi & Foladori; Maclurcan, 2008; Lane & Kalil, 2005; Shapira & Youtie, 2014). The exponential growth of nano-enabled products and their various nano-market segments have motivated studies that project nanotechnology as the engine of the next *Schumpeterian wave* of economic development (Islam & Miyazaki, 2009; Roco, 2017; Tuncel, 2015). In addition, the recent period has been referred to by some authors as the *nano-century* (Dhawan et al., 2009).

The international literature examining the rise and establishment of nanotechnology indicates that the US nanotechnology initiative sparked a global race for this technology. This led governments worldwide also to develop national initiatives (Dong et al., 2016; Tolochko, 2009; Shapira; Youtie, 2011; Invernizzi et al., 2019).

In this article, "national strategy," "national initiative," or "national policy" refers to the set of actions aimed at promoting and spreading nanotechnology in a specific country or territory.

The analysis will focus on the nanotechnology initiatives of the five largest emerging economies, which are part of a semi-institutionalized political group known as BRICS (Stuenkel, 2017). Literature often depicts these countries as having significant scientific development but a more limited path in terms of innovation (Cassiolato et al., 2008; Kahn, 2015; Pina, 2009).

METHODOLOGY

The study methodology was divided into two parts. First, a bibliographical and documentary research was conducted to position the object of analysis in relation to other related studies (Tight, 2019). This involved reviewing articles, theses, monographs, and reports from international organizations to identify trends in STI policies promoting nanotechnology within the BRICS countries. This section aimed to present the historical trajectory of these countries in developing their national nanotechnology initiatives, highlighting the state's role in the process and the key institutional structures adopted. Additionally, it mapped some movements around the initiative and its public policy form, both in terms of the actors involved and the macro-political and economic environment.

The second phase was inductive-interpretative in nature, starting from specific and empirical observations towards the search for theoretical meanings through reflexive narratives (Bell, et al. 2022). Data from the StatNano database was analyzed to compare the number of scientific articles published in journals indexed in the Web of Science (WoS) among the BRICS countries. The analysis focused on the period from 2016 to 2021 and estimated the nanotechnology Activity Index (AI). In simple terms, AI represents the ratio of a country's publication output in nanotechnology to its publication output across all research areas (Rousseau, 2018). The global Activity Index is set at one (1), so the AI for a specific country during a specific period can be calculated using equation (1) below:

$$AI = \frac{x}{w} \qquad (1)$$

Where ***AI*** represents a country's Activity Index in a given technology, ***X*** represents the proportion of nanotechnology publications by that country in the period, and ***W*** represents the worldwide proportion of nanotechnology publications. An Activity Index greater than 1 indicates a higher proportion of nanotechnology publications, strongly emphasizing this field. On the other hand, an AI of less than 1 suggests a lower focus on nanotechnology. Nevertheless, AI has limitations and should be interpreted within a broader context of qualitative and quantitative assessments regarding the dynamics of scientific publication and their STI policy incentives.

RESULTS AND DISCUSSION

This section analyzes the trajectory of each national nanotechnology initiative. It considers government actions, the institutional frameworks established, and the expected outlook of the programs and policies. Subsequently, an index of nanotechnology activity for the five countries in focus is estimated and discussed.

Brazil's Nanotechnology Initiative

The inclusion of nanotechnology as a strategic agenda in the Brazilian STI context came about as a result of various actions undertaken in the first decade of the 2000s (Fernandes & Filgueiras, 2008; Knobel, 2005; Invernizzi, Foladori & Quevedo, 2019; Peixoto, 2013). The establishment of the initial nanotechnology research networks was partly due to the increasing involvement of Brazilian scientists on the global stage (Invernizzi, Hubert & Vinck, 2014). On the other hand, the rapid diffusion of nanotechnology was related to the agility of researchers and nano-enthusiasts to articulate and publicly promote the potential benefits of this technology in various media platforms, ranging from the scientific-academic context to mass media such as television and public discussion forums (Invernizzi, 2008; Korbes, 2013; Pontes, 2017). Notably, government intervention played a significant role in this early phase, with federal organizations such as the National Council for Scientific and Technological Development (CNPq), the primary public funding body for Brazilian science, initiating the first funding programs in 2001 to establish networks of researchers in the field of nanoscience (Knobel, 2005).

The main result of this first wave of action by nanotechnology groups and networks in Brazil was the Nanoscience and Nanotechnology Development Program, submitted for public consultation and formally incorporated by the Minister of Science and Technology (MCTI) into the Multi-Year Plan (PPA)[1] for 2004-2007 (Knobel, 2005; Invernizzi, Foladori & Quevedo, 2019). This program focused on four main areas of action: i) the establishment of nanotechnology laboratories, infrastructure, and networks; ii) technical and financial support for these laboratories and networks; iii) the promotion of institutional nanotechnology R&D projects; and iv) funds for the operational management of the program. In 2005, Brazil launched the National Nanotechnology Program (PNN). This initiative relied on resources from sectoral funds, which progressively increased the MCTI's investments in nanotechnology, increasing the number of subsequent nano-initiatives (Plentz & Fazzio, 2013). This marked the beginning of the "nano-boom" in Brazil (Invernizzi, Foladori & Quevedo, 2019), characterized by a surge of political-technological enthusiasm that drove the development of new initiatives to promote nanotechnology in the following years.

Following the development of initial scientific and technological capacities, the Brazilian Nanotechnology Initiative (IBN) was launched in 2012 and implemented in 2013. The foundation of this initiative was the creation of the National System of Nanotechnology Laboratories (SisNano), which is a network of laboratories providing facilities and human resources to both public and private users. This multi-user strategy aimed to foster greater interaction between public and private sector players and generate new processes and products in nanotechnology, thereby enhancing the country's competitiveness (Plentz & Fazzio, 2013; Invernizzi, Foladori & Quevedo, 2019). It should be noted that in 2012, the Brazil-China Center for Research and Innovation in Nanotechnology was created, a public entity designed to coordinate international cooperation between the two countries to develop the nano sector (Ferreira-Pinto, 2019).

Within the argumentative rhetoric of the initiatives and programs launched before and during the construction of the IBN, it is possible to perceive the wave of enthusiasm for nanotechnology in official documents conceived as a future-bearing technology or as a frontier for innovation (Invernizzi, Foladori & Quevedo, 2019). In fact, Nanotechnology has been identified as a strategic area in Brazilian national STI plans, such as the Science, Technology, and Innovation Action Plan (PACTI) from 2007 to 2010, and in industrial policies like the Industrial, Technological and Foreign Trade Policy (PITCE) from 2004 to 2008, and the Productive Development Policy (PDP) from 2008 to 2010 (Invernizzi, Korbes & Fuck, 2012).

Despite significant advances in basic infrastructure and the development of scientific and technological capabilities, as well as the consistent prioritization of nanotechnology in Brazilian STI policy plans, there is evidence of recurring irregularities in the budget allocation of this national initiative, which raises questions about their material rationality. In a study by Barbosa, Bagattolli, and Invernizzi (2018), the trajectory of non-reimbursable financial instruments applied to nanotechnology since 2006 is depicted. This coincides with the launch of the Economic Subsidy for Innovation (SEI) program. In its inaugural year, the SEI program allocated a nominal volume of R$12 million to nanotechnology projects. The following year saw a substantial increase, with the allocation reaching a peak of R$30.8 million.

However, in 2008, the funds dropped significantly to R$4.3 million, and this downward trend continued in 2009 and 2010. The SEI program did not make any investments between 2011 and 2012. However, in 2013 (the year the IBN was implemented), the funding returned to its initial levels, reaching approximately R$26 million allocated for nanotechnology. This recovery was short-lived, as in the following years (2014 to 2016), there were no funds allocated for nano projects from the SEI (Barbosa, Bagattolli & Invernizzi, 2018).

Given the trajectory of Brazil's nanotechnology initiative, it is possible to detect a kind of short cycle of "enthusiasm" that leverages the development of scientific and technological actions and capacities and which, to a certain extent, allows for a far-reaching projection for the country's nano-scientific and technological future. However, these moments of enthusiasm seem to be constantly interrupted by instability in budget allocations. It should be noted that in the years following the launch of the IBN, Brazil's political and macroeconomic situation was characterized by recurring crises (Barbosa, 2017; Bastos, 2017). This context of instability also impacted the STI sphere (De Souza & Da Silva, 2016; Buainain, Corder & Bonacelli, 2017), resulting in reduced investment and, in recent years, even the undermining and weakening of scientific efforts (Carvalho, Carvalho & Zagni, 2020).

This context of recent crisis and uncertainty is also reflected in the material support for BNI, since the federal government's projected budget to promote nanotechnology in the country for 2020 was only R$2.2 million (Dias et al., 2021), less than 10% of the amount allocated by the SEI program to nanotechnology projects in 2006. Although nanotechnology remains a national priority in political rhetoric for R&D and innovation projects for the 2020-2023 horizon (MCTI, 2019), the situation of scarce resources and progressive budget reductions creates a context of permanent tension for scientists competing for public funding to continue developing projects at ICTs (Invernizzi, Foladori & Quevedo, 2019). This illustrates the non-linear nature of innovative processes and the significant influence of the institutional context on the development of emerging technologies.

[1] It defines the guidelines, objectives and goals of the Brazilian federal public administration.

Russia's Nanotechnology Initiative

Between 1990 and 2010, Russia faced major institutional transformations in the field of science and technology, mainly due to its post-Soviet modernization process, which implied greater openness and collaboration with international research networks but almost always preserved the traces of state centralization concerning funding STI activities (Graham & Dezhina, 2008).

In this context, Russia's nano initiative had its beginnings in 2004, when the government included nanotechnology in the Federal Targeted Program (FTP) of Science and Technology[2] , as a strategic response to the movement of developed and developing countries (Karaulova, et al., 2016). However, initial efforts were rather cautious and were later overshadowed by the formulation of a more comprehensive National Nanotechnology Development Strategy (NNDS) launched in 2007 (Connolly, 2013).

The central objective of Russia's 2007 NNDS was to direct financial and organizational resources towards fundamental research in nanotechnology, with the ultimate aim of creating a competitive domestic market for nano-enabled products (Gokhberg, Fursov, Karasev, 2012). In other words, the Russian government intended to industrialize and commercialize scientific research results from the beginning of the NNDS. In this regard, new institutional bodies were designed to carry out the strategy, such as a Supervisory Board and a State Corporation[3] (called *Rusnanotekh and* later RUSNANO) to develop a national nanotechnology industry (Connolly, 2013). In terms of money[4], around 100 billion rubles (equivalent to 3.3 billion US dollars at the time) was planned to be provided as public funding for the period 2007-2015.

The significant allocation of resources by the Russian government for nanotechnology clearly highlights the relevance and impact of this technology in shaping STI public policy[5] between senior bureaucrats and decision makers (Karaulova, et al., 2016; Connoly, 2013). Another indication of the government's aspirations was the targets set for the ENDN, which aimed to more than double the annual sales of nano-industry products (from USD 0.7 billion in 2008 to USD 1.5 billion in 2015). Despite the initial enthusiasm for the nanotechnology initiative, there were significant institutional reforms at the core of the RUSNANO CTI policy implementation process within its first five years. The literature suggests that the government overestimated the capacity of the Russian scientific system to generate lucrative research (Terekhov, 2013). Furthermore, there was limited industrial progress in creating domestic markets for nano-enabled products (Gokhberg, et al., 2013) and low international competitiveness (European Commission, 2013).

In 2012, RUSNANO was reorganized as a joint-stock company. This trend continued in subsequent years for the rest of the State Corporations (Karaulova et al., 2016). This wave of institutional reforms also affected other spheres of the science and technology system, as with the establishment of new funding procedures based on donations from the private sector. It's important to note that in this first restructuring of RUSNANO, the state still held 100% of the shares (Connoly, 2013).

In recent years, the Russian authorities have identified issues with standardization and certification in the nanotechnology industry, potentially impacting the measurement of indicators and the perception of innovative results in the country (Inshakova; Inshakova, 2020). However, Ganichev and Koshovets (2018) have criticized the Russian federal government's narrative, arguing that there is no fully developed nanotechnology industry in the country and that it is merely a "statistical phenomenon" promoted by the government. The authors also note that accurately identifying the genuine growth segments of the nanotechnology industry in Russia is currently not feasible, and:

"...the accurate measurement of the real growth rates of the Russian nano-containing products industry will be possible after the reduction of intensive government support. This will occur when the primary formation of the industry is completed and the new enterprises develop using their capital." (Ganichev; Koshovets, 2018, p. 19).

Recent budget plans still prioritize nanotechnology for Russia's national CTI policy, but reductions in direct funding have already been evidenced[6] (Golubev, et al, 2018). On the other hand, the Russian government has started to encourage the nano sector through tax exemptions, subsidies for innovation projects, attracting foreign capital, venture funds, and the banking sector (Golubev, et al., 2018; Ganichev & Koshovets, 2018; Lamberova, 2020). This could be seen as an attempt to encourage private investment in R&D and improve competitiveness. The focus is now moving away from the traditional innovation policy model centered on universities and the government (Terekhov, 2019; Lamberova, 2020).

[2] Targeted Federal Programs (in Russian, *Federal'nyye Tselevyye Programmy*) are among the main instruments for implementing government policies related to the long-term development of science and technology in Russia. The main role of this instrument is to coordinate activities in a specific field, as was the case with nanotechnology, identified at this stage as an area that required political action (Connolly, 2013).

[3] These State Corporations (in Russian *goskorporatsii*) were state-owned holding companies that were created under a special regime during V. Putin's second term as president (2004-2008). According to Malle (2012), these organizations did not have a commercial character like other large Russian state-owned companies and as a rule were run by managers appointed by the government, as well as enjoying tax and tariff preferences.

[4] Data from the official document: *Development program for the nanoindustry in the Russian Federation to the year 2015* released in 2007.

[5] Some authors attribute this to the lobbying and influence of some prominent scientists in the country, such as the renowned scientist Mikhail Kovalchuk, brother of the banker Yury Kovalchuk, who has been identified as one of the main financiers of the Putin government (Josephson, 2009; Dobrovidova, 2016).

[6] Draft Law 15455-7 on the Russian national budget for 2017-2019 already provided for cuts in direct funding for some STI programs (GOLUBEV, et al., 2018).

India's nanotechnology initiative

Despite having lower levels of total R&D spending than its BRICS peers, India has been gaining prominence in the context of nanotechnology, especially in the context of international scientific publications (Ramani, et al, 2011; Samal, Manohara, 2019). Most of India's nano initiatives are permeated by government presence and mediated by public research institutions, mainly focusing on basic research into nano-materials (Beumer & Bhattacharya, 2013). Another critical aspect of the Indian nanotechnology initiative is society's apparent acceptance (BEUMER, 2019), which ends up enabling progressive public investments and promotion actions.

Nanotechnology became a part of India's science and technology policy agenda during the 9th Five-Year Plan (1998-2002) and was identified as a promising and priority technology for the nation's development (Kumar, 2014). The launch of the Nanoscience and Technology Initiative (NSTI) during the 10th Five-Year Plan (2002-2007) provided significant impetus for the first concrete nanotechnology development projects in India to take off (Kumar, 2014). The Department of Science and Technology (DST) is the central entity responsible for creating, financing, and executing nanotechnology plans and initiatives in the country[7].

The NSTI focused on developing basic infrastructure and initial capacities for the growth of nanotechnology in India (Kumar, 2014; Beumer & Bhattacharya, 2013). According to Beumer (2019), the NCTC found an opportunity in the Indian political context through the engagement of the then Head of State Abdul Kalam and influential scientists at the top level of power, such as the prominent chemist C. N. R. Rao. The positive results of the NSTI allowed the initiative to continue in 2007 with an umbrella program called Nano Science and Technology Mission (NSTM), which was included in the technology policy of the 11th Five Year Plan.

The NSTM was a comprehensive initiative that included new goals for the Indian nanotechnology program. These goals encompassed seeking international cooperation, establishing public-private partnerships, creating a regulatory framework for nanotechnology in the country, and focusing on the development of highly trained human resources (Ramaraju, 2012; Kumar, 2014; Samal & Manohara, 2019). One of the significant outcomes of the NSTM was the establishment of 20 centers of excellence in nanotechnology across various states in India, as well as the launch of at least 17 new undergraduate and postgraduate programs in nanotechnology (Bhattacharya, Jayanthi & Shilpa, 2012; Sundararajan, 2012). Additionally, several international cooperation agreements were formed with at least 25 countries (DST, 2016; Ramaraju, 2016). The NSTM remained a relevant policy under the 12th Five-Year Plan (2012-2017) and continued as NSTM II.

In the recent phase, NSTM II has been focusing more on promoting applied R&D to create new nano-processed products, processes, and useful technologies (Kumar, 2014; Beumer & Bhattacharya, 2013). Additionally, the involvement of the private sector has been increasing in recent years, especially in the industrial sector with R&D activities in nanotechnology (Singh & Sengar, 2020; Pandey, 2018; Beumer, Bhattacharya, 2013; Beumer, 2019). Another NSTM II initiative reflecting the closer ties with the market was the establishment of India's first nanotechnology business incubator in 2017, aiming to strengthen public-private partnerships[8] (Bhatia, Vasaikar & Wali, 2018).

The Indian nanotechnology initiative was initiated through centralized efforts led predominantly by the state. It is evident from the Indian case that political acceptance, particularly at the top of the bureaucracy, and social acceptance of nanotechnology as a solution to societal issues are vital for the sector's development in emerging countries. In the recent phase of the initiative, there has been a deliberate shift towards a policy approach centered on "missions," emphasizing the need to increase private sector participation and enhance the economic complexity of the nanotechnology sector through the production of nano-enabled goods, thereby driving technology-intensive growth in the country.

China's Nanotechnology Initiative

In the 1990s, China began making public investments in nanotechnology R&D. The national initiative gained momentum in the early 2000s, driven in part by the goal of competing internationally in nanotechnology with major Western powers. To coordinate efforts, a National Committee for Nanoscience and Technology was established[9], and the first National Nanotechnology Development Strategy was formulated for the 2001-2010 period (Jia, Zhao & Liang, 2011). The main focus of the initiative was on basic science, with the strategic objective being the commercialization of nanotechnology through research and development. Initial efforts also concentrated on establishing essential infrastructure and developing human capital (Liu & Zhang, 2007). The long-term vision of the Chinese nanotechnology initiative included the training of

[7] The DST is a department of India's Ministry of Science and Technology. It was set up in 1971 to promote new areas of science and technology and play the role of the central body for coordinating and promoting scientific and technological activities in the country.

[8] The investment used to create the *Nanotech Research Innovation and Incubation Center* (NRIIC) was 50% public and 50% private, and in addition to the participation of the DST, there was also cooperation from the *National Science & Technology Entrepreneurship Development Board.* By the beginning of 2020, it is estimated that at least 80 companies, including nanotechnology start-ups and spin-offs, will have been incubated at the NRIIC (Ramar, et al, 2020).

[9] The event was attended by officials from different areas of the Chinese public administration and the Ministry of Science and Technology, along with representatives from the country's leading R&D promotion institutions (Jia, Zhao & Liang, 2011; Peixoto, 2013).

scientists(Peixoto, 2013), and it was strategically important to attract highly qualified professionals from other countries. International cooperation was also seen as integral to the restructuring of higher education institutions to meet the standards of high competitiveness in science, technology, and education[10] (Wang et al., 2012; Wang et al., 2013; Zheng et al., 2014).

The involvement of Chinese researchers in collaborations with scientists from prestigious nanotechnology centers worldwide was crucial in addressing the lack of scientific credibility that had previously affected the publication of Chinese research in leading Western journals (Leung, 2013). This engagement was also evident in partnerships between major global technology companies[11]. Furthermore, this international involvement served as a means for Chinese scientists to acquire knowledge and skills from interactions with researchers from countries with more robust intellectual property regulations. According to Leung (2013), this resulted in a shift in focus for these individuals, leading to the development of "business skills" for product development rather than solely focusing on publishing articles.

By the end of the first decade of the 2000s, China successfully overcame the key barriers to adopting new technology, as identified by Perez and Soete (1988), for countries that were slower to embrace it. In other words, at this time in history, China's nanotechnology initiative had already met the minimum requirements for fixed investments[12], the development of scientific and technological knowledge[13], and the acquisition of relevant experience and skills[14].

The Chinese case stands out among emerging countries for its international leadership in science and technology. This is evidenced by increasing public investment in R&D, a high proportion of international patent applications, and a leading position in the number of international scientific publications (Wilsdon, 2007; Yip & Mckern, 2014; Huang & Harif, 2015; Dovgal et al, 2019). In the area of nanotechnology research, China has made significant progress over the last decade, narrowing the gap with the United States of America (USA), the current global leader (Dong, et al., 2019; Kostoff, 2011). This success is the result of a wide-ranging strategy involving substantial public investments in infrastructure, institutional restructuring of the educational and scientific sectors to develop better human capital, and the strategic integration of Chinese researchers into major international research networks.

However, as noted by Huang and Wu (2012), the Chinese nanotechnology initiative is primarily focused in universities and public research institutions, with limited connections to industry. This makes it challenging for local companies to benefit from the substantial public investments in R&D in the short term. Despite this, there are no indications that the state is willing to decentralize or relinquish its leading role in coordinating the strategy. This stance is evident in a speech by Bai Chunli, a prominent scientist, nanotechnology enthusiast, and former president of the Chinese Academy of Sciences (CAS) in 2017: "...*We will strengthen the strategic landscape and top-down design for developing nanoscience, which will contribute greatly to the country's economy and society*". In other words, once there are favorable results in the policymakers' view, "there would be no reason" to think of a bottom-up strategy for the Chinese nanotechnology initiative.

South Africa's nanotechnology initiative

According to Harsh et al (2018), South Africa's nanotechnology strategy began in 2002 with a *bottom-up* initiative by scientists specialized in the field who formed a network called *South African Nanotechnology Initiative* (SANI). This first effort consisted of an inventory of the country's nanotechnology infrastructure and human capital capabilities. Later, in 2006, a partnership between SANI and the Department of Science and Technology resulted in the launch of South Africa's first National Nanotechnology Strategy .

In 2002, South Africa's nanotechnology strategy started with a *bottom-up* initiative by specialized scientists who formed a network called the South African Nanotechnology Initiative (SANI) (Harsh et al., 2018). This initial effort involved creating an inventory of the country's nanotechnology infrastructure and human capital capabilities. In 2006, a partnership between SANI and the Department of Science and Technology[15] led to the launch of South Africa's first National Nanotechnology Strategy, marking a significant milestone in the country's nanotechnology development.

The strategy aimed to achieve three primary objectives:

[10] One of the main challenges the Chinese nanotechnology initiative faced was the significant asymmetry between the national elite universities and the universities within the country. To promote the development of science and technology in inner-city universities and less developed regions, the government strongly promoted international trips by researchers from these universities to renowned institutions in the major Western powers (Tang, 2013).

[11] One example is the partnership between Tsinghua University and *Foxconn Nanotechnology Research Center*. The investment provided by the company has allowed the university to conduct nanotechnology research while benefiting from Foxconn's global reputation. Cf Tsinghua (2010).

[12] Total gross expenditure on R&D rose from 1.2% of GDP in 2004 to 2.02% in 2014 (WORLD BANK, 2021), surpassing all its BRICS peers and significantly reducing the gap with the United States.

[13] China has a growing share of total scientific publications and patent filings. Specifically, in the case of nanotechnology, patenting increased by approximately 57% between 2009 and 2014 (Statnano, 2021).

[14] As mentioned in the previous section, China has developed a significant strategy for the external insertion of its researchers and its educational system, which has also involved the participation of large multinational industries in high-tech sectors.

[15] Currently called the *Department of Science and Innovation* (DSI), the South African government department is responsible for scientific research, including space programs.

(i) the development of human resources and support infrastructure;

(ii) support for the creation and generation of new products;

(iii) support for long-term nanotechnology projects, considered emblematic for demonstrating the benefits of this technology in society (Cele, Ray & Coville, 2009; Harsh et al., 2018). The initiative was projected to be implemented over a 10-year period from its launch in 2006.

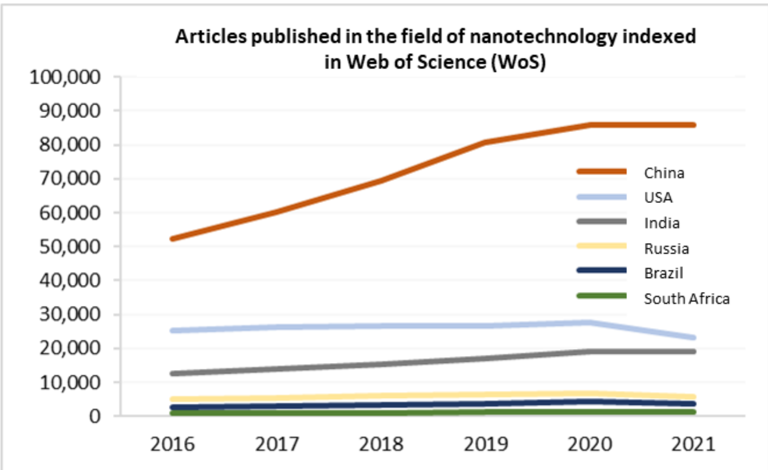
As an emerging country, South Africa has focused on nanotechnology as a catalyst for economic development and addressing social challenges. This objective has been a key aspect of the rhetoric used by SANI members to advance the national strategy in the political arena (Harsh et al., 2018; Gastrow, 2009). Regarding financial resources, it is estimated that the South African nanotechnology initiative allocated approximately USD 75 million in the first decade. From the perspective of Saidi and Douglas (2017), the main challenge lies in measuring the impact of these investments in nanotechnology on South African development, which is crucial for evaluating the effectiveness of this STI policy.

On the other hand, Masara, Van der Poll and Maaza (2021) analyzed the recent performance of nanotechnology in terms of scientific research in South Africa, pointing out that the total number of publications in the field increased from 1.4% in 2000 to 6.6% in 2019. Furthermore, the presence of the private sector is still limited, with little participation in nanotechnology R&D activities and low university-industry interaction (Harsh et al., 2018). Looking at the production chain, South African nanotechnology remains concentrated in nano-materials and nano-intermediates (Masara, Van Der Poll & Maaza, 2021). It can be said that the South African initiative is still in the early stages, especially when considering scientific publications.

Recent nanotechnology scientific production in the BRICS

Recent trends in international scientific production in nanotechnology indicate that China is emerging as a global leader, surpassing the historical leader, the USA. The number of Chinese publications indexed in WoS has grown exponentially in recent years, making the country the main generator of published research since 2016. Similarly, India has been climbing the international publication rankings, although with a less significant trajectory in terms of publication growth and lower relative spending on R&D. This also reflects the increasing prominence of nanotechnology in India (Beumer, 2019) and its broad social acceptance. Figure 5 illustrates this publication trend for the period 2016-2021.

Figure 1. International scientific production in the field of nanotechnology



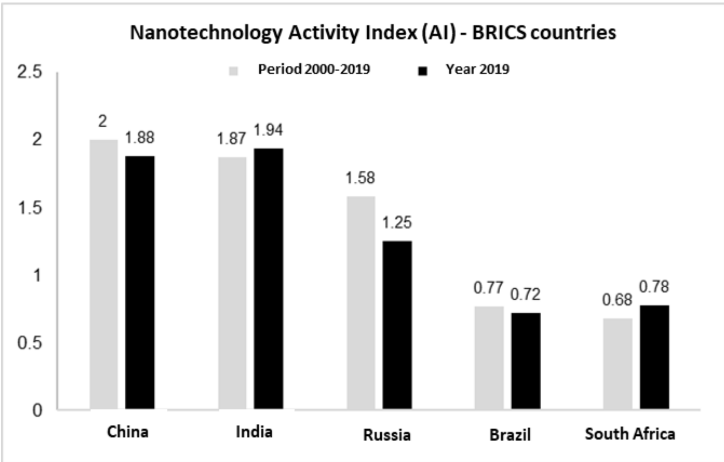
Source: Authors' development using StatNano and WoS data

When observing Figure 5, it is evident that there has been a recent decrease in the number of publications by the United States and a lack of growth in the rest of the BRICS countries, including Brazil. However, it's important to interpret this publication indicator with caution, as there are significant population variations among the countries being analyzed. Therefore, the Activity Index in nanotechnology could serve as another metric to strengthen the evidence of international involvement and recent improvement in the performance of China and India within the BRICS context.

When examining the BRICS countries over the last two decades (2000 to 2019), China has been the most productive with an AI of around 2, followed by India and Russia with AIs of around 1.87 and 1.58, respectively. During the same period, Brazil and South Africa had AIs of 0.77 and 0.68, respectively. In 2019 data, it is evident that India had a higher AI output than China. This could be explained due to the growth and international integration of Indian scientific production. In addition, this trend could be connected to the findings of Pandev and Pansera (2020), which suggest that Indian nano-scientists tend to focus on research topics with publication themes from developed countries. In the case of South Africa, its AI output in 2019 exceeded the average of the two previous decades, indicating a recent increase in the volume and visibility of scientific production in nanotechnology.

Also in 2019, both Russia and Brazil exhibited lower levels of AI compared to the average of the two decades. This may be attributed to changes in the focus and institutional framework of nanotechnology research in Russia, particularly with the introduction of RUSNano. In the case of Brazil, there has been a recent decline in the country's nanotechnology initiative following a decade of significant progress (Invernizzi, Foladori & Quevedo, 2019). Despite Brazil having one of the most advanced nanotechnology programs in Latin America (Kay & Shapira, 2009), its research direction continues to be predominantly influenced by national and non-commercial collaborations (Kay & Shapira, 2009; Chinchilla-Rodríguez, Ocaña-Rosa & Vargas-Quesada, 2016; Kay & Shapira, 2011). In Figure 2, the following summary presents the AI insights of the BRICS countries over the period of 2000-2019 compared to their performance in 2019.

Figure 2. Mapping the Nanotechnology Activity Index (AI) of the BRICS countries (2000-2019)



Source: Source: authors' estimations using data from StatNano and based on Rousseau (2018) and Masara, Van Der Poll and Maaza (2021) approaches.

The comparative review has revealed that the BRICS countries have made noteworthy advancements in their respective national nanotechnology initiatives, positioning some of them as global leaders, particularly in terms of scientific production. As with any emerging technology, nanotechnology presents inherent risks and uncertainties, along with substantial costs associated with its effective progression and application across diverse domains, be it in enhancing capabilities or in the advanced stages of nano-enabled products (Roco, 2017; Tuncel, 2015). The process of acceptance and legitimization entails the involvement of influential sector leaders, who can be perceived as genuine political entrepreneurs (Justo-Hanani, 2015). One approach to fortifying this process from the standpoint of key actors in the STI policy and context, is to advocate for the continual integration of nanotechnology transcending its futuristic vision and rationalizing it through tangible permanent institutionalization. In that direction, Ometto et al. (2024) have proposed a potential framework for naturalizing this nanotechnology agenda.

The ability to generate market value greatly depends on the efforts directed toward national nanotechnology initiatives. These initiatives should aim to create an environment that fosters entrepreneurial incentives and promotes the growth of the nanotechnology market. According to existing literature, bottom-up innovation strategies such as open innovation and increased collaboration between universities and companies (Pujotomo et al., 2023; Bejarano et al., 2023) are crucial for the development and consolidation of emergent technologies. In addition, it is important to refine technology transfer mechanisms and establish institutional frameworks that are conducive to the emergence of start-ups and spin-offs in the nanotechnology field. Given the vast territories of the BRICS countries, it is likely that subnational initiatives will start to emerge once a national nanotechnology strategy is established[16]. This will create new decentralized opportunities that can also be tailored to meet the specific needs of local communities in developing countries. To support these initiatives, national governments need to provide resources and transfer knowledge to local administrations without imposing strict control, but rather by offering support to progressively overcome the national state-led strategy towards a model increasingly open to new forms of governance.

[16] A notable case is that of Pennsylvania in the United States, where the state successfully developed its own strategy for regional nanotechnology development (Sa et al., 2008).

FINAL REMARKS

The BRICS countries have historically been at the forefront of nanotechnology initiatives, with the government playing a significant role. These initiatives are mostly top-down, but there is some institutional heterogeneity in how they are developed and executed. Geopolitics also influences these initiatives, especially in countries vying for international leadership against Western powers. China and India have emerged as leaders challenging Western dominance in scientific production. However, both countries face limitations and barriers to creating value beyond research. Russia has shifted towards a more entrepreneurial approach, as evidenced by the introduction of venture capital-type policy tools, which may explain the decrease in its Activity Index. Brazil's nanotechnology initiative is a driving force in Latin America, but macro-political processes can hinder its progress towards a more advanced and profitable stage. South Africa's nanotech initiative, although less prominent, has shown recent growth and could benefit from learning from the pioneers' paths.

Some evidence suggests a strong link between the involvement of researchers from emerging countries in prominent international scientific networks and the improvement of nanotechnology production in terms of quantity and visibility (Karpagam, 2014; Velmurugan & Radhakrishnan, 2018; Youtie, et al., 2016). However, in the context of emerging countries, replicating scientific and technological advancements in nanotechnology based on the standards of developed countries can overlook local needs linked to the structural realities and challenges present in less developed regions (Foladori, Figueroa, Záyago-Lau & Invernizzi, 2012). In this scenario, countries with less advanced Activity Index in nanotechnology could benefit from collaborating with the more productive BRICS countries to exchange policies and strategies for addressing social issues using emerging technologies, given the structural similarities these nations share.

The main limitation of the study was its primary descriptive nature, focusing on a general analysis of policy initiatives without deeply exploring causal relationships. Future studies could use these findings as a starting point and develop deeply empirical strategies, such as interviews with key players in national nanotechnology initiatives in the BRICS. Additionally, new research could examine local and regional nanotechnology initiatives to determine if these strategies align with the national macro policies by countries, and whether a more open and decentralized model leads to better innovative results.

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