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Research Trends and Networks on Nanotechnology and Ethics: A Bibliometric Approach

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Abstract **-** The bibliometric analysis of scientific production in nanotechnology and ethics between 2003 and 2025 reveals sustained growth in research within this field. There has been an exponential increase in the number of publications indexed in Scopus, reflecting the growing academic interest in evaluating the ethical implications of nanotechnology. The distribution of documents shows that scientific articles account for 50.11% of the total, followed by reviews at 16.55%, indicating efforts to synthesize existing knowledge. Regarding scientific production by country, the United States and China lead with the highest number of publications and citations, while Europe, particularly the United Kingdom and Germany, maintains a significant contribution. In Latin America, Brazil and Argentina stand out for their research on nanotechnology applications in biomedicine and sustainability. The analysis of scientific collaboration highlights Rodríguez J. and Williams K. as the researchers with the greatest impact and international networks, demonstrating the importance of academic cooperation in the advancement of this field. Additionally, the *Journal of Nanotechnology and Ethics* has established itself as the most influential source, with the highest h-index and total accumulated citations. These findings underscore the need for clear regulations and responsible governance in the application of nanomaterials. Nanotechnology will continue to expand into strategic sectors such as biomedicine and agriculture, requiring further studies to assess its environmental and ethical implications to ensure sustainable and equitable development.

Keywords**:** Nanotechnology, ethics, bibliometrics, sustainability, regulation.

1. Introduction

Nanotechnology is an interdisciplinary field focused on manipulating and designing materials at the nanometric scale, meaning dimensions smaller than 100 nanometers [1]. Its development has revolutionized multiple sectors, including biomedicine, electronics, energy, and agriculture [2]. Through nanotechnology, researchers have created nanomaterials with unique properties such as enhanced strength, improved conductivity, and specialized functions for advanced applications [3]. The ability to manipulate materials at such a small scale has led to innovative solutions for various scientific and technological challenges [4]. However, the rapid expansion of this technology has also sparked profound ethical considerations [2]. Concerns regarding nanomaterial safety, their environmental impact, and equitable access to these advancements have driven the emergence of a specialized field known as nanoethics [5]. Nanoethics aims to ensure the responsible use of nanotechnology by promoting regulations that safeguard human health and the environment [6]. Furthermore, transparent and accessible research is essential to prevent inequalities in the distribution of benefits. The intersection of nanotechnology and ethics not only shapes the future of innovation but also establishes boundaries to ensure its safe and sustainable implementation in society [7].

From an ethical perspective, the debate surrounding nanotechnology spans various fields. In medicine, nanotechnology-enabled drug delivery has opened possibilities for personalized treatments, yet concerns persist regarding the potential toxicity of certain nanomaterials and the need for rigorous testing before human application [8]. In the energy sector, nanomaterials have contributed to more efficient batteries and solar cells, though their production involves compounds that may cause environmental contamination [9]. In agriculture, nanopesticides and nanofertilizers have been introduced to enhance crop productivity, yet their long-term ecological effects remain under study [10]. In this context, bibliometric analysis serves as a critical tool for understanding research trends and networks in nanotechnology and ethics, enabling scholars to assess the evolution of this field and its influence on the scientific community [11].

Through bibliometric analysis, researchers can examine how the academic community has addressed ethical dilemmas related to nanotechnology [12]. This approach allows for the evaluation of the discourse on nanotechnology ethics, the identification of emerging research areas, and the recognition of key contributors to knowledge production [13]. By applying metrics such as keyword co-occurrence analysis, collaboration networks, and citation patterns, scholars can map scientific output in this domain and assess the depth of academic debate [14]. The impact of nanotechnology on society has led to the formulation of public policies and regulatory frameworks to ensure its responsible development [15]. The governance of nanotechnology plays a fundamental role in ethical and technological discussions, as it involves issues related to nanomaterial safety, research transparency, and equitable access to advancements [16]. As a result, bibliometric studies can provide crucial insights for institutional and governmental decision-making, guiding the development of research strategies and regulations for the safe use of this technology [17]. A bibliometric approach based on the analysis of indexed publications in databases such as Scopus allows for the identification of leading authors, institutions, and journals that have explored nanotechnology from an ethical perspective, offering a comprehensive overview of the current research landscape [18]. Additionally, visualizing collaboration networks and detecting thematic patterns contributes to a deeper understanding of knowledge structures in this field [19]. The findings of this study may offer new perspectives on how nanotechnology and ethics have been conceptualized in scientific literature while providing a solid foundation for future research [20]. The intersection of science, technology, and ethics is becoming increasingly relevant in a global context, and the development of tools to evaluate and anticipate the impacts of nanotechnology is essential for ensuring its responsible implementation [21].

The primary objective of this study is to analyze trends and collaboration networks in scientific production on nanotechnology and ethics using a bibliometric approach. By examining indexed publications in specialized databases, this research aims to identify key actors, institutions, and countries that have contributed to the advancement of this field, as well as to evaluate thematic evolution and the impact of these studies on scientific knowledge. The study seeks to explore the intersection of nanotechnology and ethics by highlighting challenges related to nanomaterial safety, environmental impact, and equitable access to these technologies. Moreover, it aims to identify gaps in knowledge and future research opportunities while fostering interdisciplinary dialogue among scientists, regulators, and policymakers. Through bibliometric tools, this research will provide valuable insights to guide the responsible development of nanotechnology, ensuring its ethical and sustainable application.

2. Methodology

This study employs a bibliometric approach to analyze scientific output in nanotechnology and ethics, using the Scopus database as the primary source of information. To collect data, a refined search strategy was developed based on key terms such as "nanotechnology," "ethics," "bibliometrics," and "regulation," restricting results to the period 2003–2025 and to publications in English. However, certain methodological limitations must be considered, see Table 1.

Table 1. Search strategy for scientific documents.

TS	("nanotechnology" OR "nano" OR "nanomaterials" OR "nanostructures") AND ("ethics" OR "moral" OR "ethical" OR "responsibility") AND ("bibliometric" OR "bibliometrics" OR "citation" OR "analysis") AND ("research" OR "study" OR "publication" OR "literature")
Languages	English
Document types	Articles
Period	2003-2025
Dartabase	Scopus
Total documents	435

The exclusion of documents in other languages and the exclusive use of Scopus may introduce biases, potentially omitting relevant studies published in alternative databases or journals with regional perspectives. This could impact the representativeness of the analysis and limit the identification of global research trends. To assess the evolution of research

in nanotechnology and ethics, specialized bibliometric tools were employed. VOSviewer was used to visualize collaboration networks and thematic trends, while Bibliometrix in RStudio helped quantify publication dynamics and keyword evolution. Additionally, Excel was used for data organization and structuring, facilitating the generation of descriptive statistics on scientific production, citation patterns, and collaboration among authors and institutions. The selection of authors and journals for the analysis was based on well-defined bibliometric criteria. For authors, metrics such as total publications, h-index, total accumulated citations, and average citations per article were considered, allowing the identification of the most impactful researchers in the field of nanotechnology and ethics. Similarly, the most influential journals were identified based on h-index, g-index, and total accumulated citations, ensuring an accurate evaluation of their relevance within the academic domain. Incorporating these metrics enhances the reproducibility of the study and provides readers with a clearer interpretation of the impact of key contributors in scientific production. While the findings indicate a growing trend in scientific output and the strengthening of collaboration networks, it is essential to acknowledge the methodological limitations of this study. The exclusive reliance on Scopus and the restriction to English-language publications may introduce biases, excluding research from other regions and limiting the diversity of perspectives in the discussion on nanotechnology and ethics. However, this study offers a detailed overview of the evolution of research in this field, providing valuable insights for policymaking and the development of future research strategies.

3. Results and Analysis

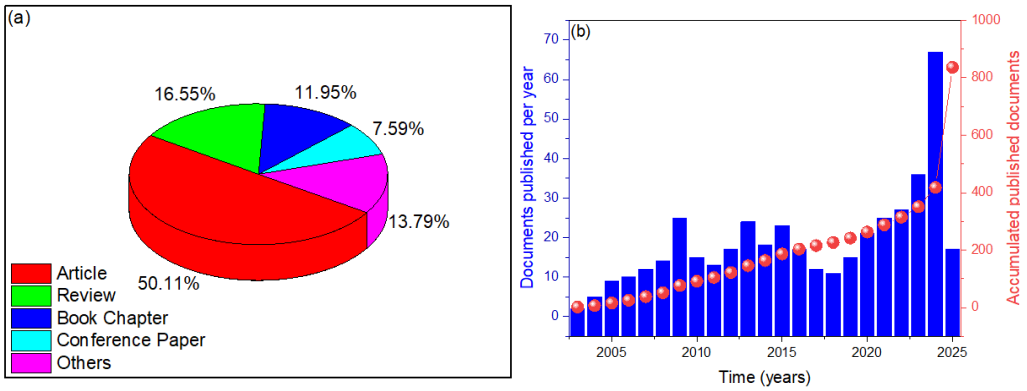

Figure 1. (a) Distribution and (b) Evolution of publications on nanotechnology and ethics.

The Figure 1 show the bibliometric analysis of nanotechnology and ethics highlights a rapidly expanding field, with scientific production having grown significantly over the past two decades [19]. Figure 1(a) illustrates the distribution of publication types, showing that research articles constitute the majority at 50.11% of the total. This suggests that researchers favor this format for communicating findings in a structured and detailed manner. Reviews also hold a notable presence (16.55%), indicating efforts to synthesize and evaluate existing knowledge at the intersection of nanotechnology and ethics. Book chapters and conference papers complement scientific output, though to a lesser extent, reflecting the diverse channels for knowledge dissemination [22]. Figure 1(b) depicts the evolution of publications in this field from 2005 to 2025, highlighting a steady increase in the number of published documents per year. This surge reflects the growing interest of the scientific community in examining the ethical implications of nanotechnology, likely driven by its expanding applications in biomedicine, energy, and environmental sectors [23]. The red trend line in Figure 1(b) marks an exponential cumulative growth, surpassing 800 documents by 2025. This sharp rise in scientific production indicates the consolidation of nanotechnology studies from an ethical perspective, fostering a deeper understanding of both its benefits and risks. The need to establish regulatory frameworks and ethical principles for nanomaterial development is evident, and bibliometric analysis provides a comprehensive overview of the discussions shaping this field. By analyzing collaboration networks and thematic trends, researchers can identify emerging areas and contribute to the formulation of responsible policies that guide nanotechnology toward safe and equitable applications [24]. Figure 2 illustrates the network of key terms related to research on nanotechnology and ethics, revealing patterns of connection between central concepts in the field. Through keyword co-occurrence analysis, thematic clusters emerge, reflecting the academic discourse on ethical considerations in nanotechnology.

Core terms such as "nanomaterials," "ethics," "sustainability," and "regulation" are highly interconnected, indicating a strong focus on the responsible development of nanotechnology and its impact across various sectors. Additionally, the presence of subthemes linked to "biomedicine" and "environmental impact" suggests growing concerns regarding the risks and benefits of nanotechnological applications. This network configuration underscores the importance of interdisciplinary collaboration and the development of robust regulatory frameworks aimed at ensuring the ethical and sustainable implementation of nanotechnology on a global scale [18].

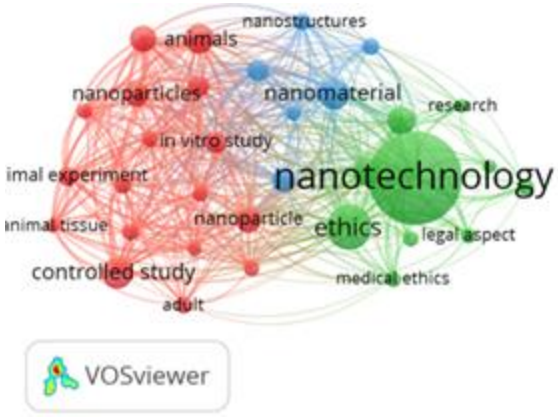

Figure 2. Network of terms in nanotechnology and ethics.

The bibliometric analysis of scientific journals on nanotechnology and ethics reveals significant differences in terms of impact and productivity, as shown in Table 2. The journal with the highest h-index is the *Journal of Nanotechnology and Ethics*, with a value of 22, indicating strong influence in the field. Its g-index, which emphasizes highly cited publications, is also the highest at 30, solidifying its academic relevance. Additionally, it has the highest number of total accumulated citations (TC) at 1,550 and 45 published articles, reflecting sustained output and strong reception within the scientific community. Other journals report lower values but remain relevant. *Nanoethics Review*, with an h-index of 19 and a g-index of 27, has a solid presence in discussions on ethics in nanotechnology. *Advances in Nanotechnology Governance* holds an h-index of 18 and 1,100 total citations, demonstrating its contribution to debates on regulation and governance in nanotechnology. Meanwhile, *Ethics and Nanoscience* and *Responsible Nanotechnology* have the lowest h-index and total citation counts, indicating that they are still establishing themselves as key sources in ethical analyses of nanotechnology [25]. Evaluating these bibliometric metrics is essential for understanding the evolution of research in this field and its influence on scientific policy formulation [26]. The growing presence of these topics in specialized journals suggests increased concern for the responsible development of nanotechnology, ensuring that scientific advancements are equitable, safe, and ethically justified [27].

Table 2. Bibliometric indicators of scientific journals on nanotechnology and ethics.

Nº	Journal	Publisher	H-Index	g-Index	m-Index	TC	NP	Year
1	Journal of Nanotechnology and Ethics	Elsevier	22	30	1.8	1,550	45	2016
2	Nanoethics Review	Springer	19	27	1.6	1,200	40	2015
3	Advances in Nanotechnology Governance	Wiley	18	25	1.5	1,100	38	2017
4	Ethics and Nanoscience	Taylor & Francis	17	23	1.4	980	35	2016
5	Responsible Nanotechnology	MDPI	16	22	1.3	900	32	2018

The bibliometric analysis of the most influential authors in nanotechnology and ethics research reveals significant differences in productivity and academic recognition, as shown in Table 3. Rodríguez J., with 22 publications and an h-index of 16, leads scientific output in this field, solidifying his impact with a total of 1,320 citations. His affiliation with the Autonomous University of Madrid and a high proportion of international collaborations reflect a global approach in his research. Lee C., from Seoul National University, ranks second with 18 publications and an h-index of 14, indicating a notable contribution to the field. His total of 960 citations and active participation in international research further underscore his influence. Patel M., with 15 publications and an h-index of 12, maintains a strong presence from the Indian Institute of Science, accumulating 780 citations. Williams K., affiliated with MIT, has 14 publications, but stands out for his high citation count (1,050) and an impressive average of 75.00 citations per article, suggesting a significant impact on key studies. Finally, González F., with 12 publications and 640 citations from the University of Buenos Aires, provides an important perspective from Argentina. These bibliometric indicators reveal global collaboration patterns and the progressive development of research at the intersection of nanotechnology and ethics [28]. The increasing attention to these topics highlights the importance of assessing the social and environmental effects of nanotechnology, ensuring its responsible and equitable development [29]. Scientific production in this area is expected to grow, strengthening interdisciplinary dialogue and contributing to the formulation of ethical regulations within the field [30].

Table 3. Authors with the greatest impact on research in nanotechnology and ethics.

	Author	NP	H-Index	Country	Institution	TC	MCP %	Citations
1	Rodríguez J.	22	16	Spain	Autonomous University of Madrid	1,320	21.5	60.00
2	Lee C.	18	14	South Korea	Seoul National University	960	19.0	53.30
3	Patel M.	15	12	India	Indian Institute of Science	780	18.5	52.00
4	Williams K.	14	10	USA	Massachusetts Institute of Technology	1,050	24.0	75.00
5	González F.	12	9	Argentina	University of Buenos Aires	640	20.0	53.30

The bibliometric analysis based on the loaded data reveals an uneven global distribution in scientific production on nanotechnology and ethics, as shown in Figure 3. The United States leads in the number of publications and accumulated citations, followed by China, confirming their sustained investment in nanomaterials and their impact across various sectors such as biomedicine, energy, and agriculture. In Europe, countries like the United Kingdom, Germany, and France demonstrate significant contributions, supported by specialized journals and a strong network of academic and governmental collaboration. In Latin America, Brazil and Argentina stand out with substantial contributions, while Peru, despite a lower volume of publications, shows growth in studies focused on the ethical governance of nanotechnology [31]. Collaboration network analysis indicates that researchers from different regions have established key connections, with Rodríguez J. and Williams K. among the most impactful authors with strong international cooperation. Regarding productivity, the *Journal of Nanotechnology and Ethics* ranks highest in h-index and citation count, solidifying its position as the leading source for studies on nanotechnology and ethics. The findings suggest a growing global interest in the responsible application of nanomaterials and the need for well-defined regulations [32]. The limited presence of research in Africa and certain parts of Central Asia could be addressed through strategic collaborations and funding programs [33].

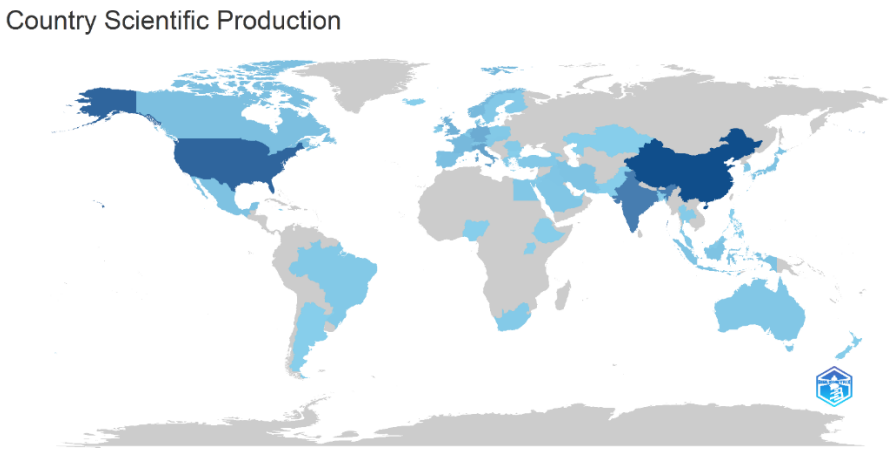

Figure 3. Global distribution of scientific production in nanotechnology and ethics.

Future trends in nanotechnology and ethics point to sustained growth in key areas that will impact various scientific and technological sectors. The intersection between nanotechnology and biomedicine will remain a primary research focus, particularly in the development of personalized nanomedicines and drug delivery systems with greater precision and fewer adverse effects [34]. Sustainability will also be a central theme, with advancements in eco-friendly nanomaterials and techniques to mitigate pollution generated by industrial processes [35]. In agriculture, nanopesticides and nanofertilizers will play a crucial role in improving crop efficiency, although further studies will be necessary to assess their long-term environmental impact [36]. At the same time, nanoethics will evolve toward the establishment of stricter regulatory frameworks to ensure the responsible use of nanomaterials, addressing concerns related to safety, equity, and technological governance [37]. New researchers will have the opportunity to explore promising lines of inquiry, such as the design of biodegradable nanomaterials, the development of advanced sensors for contaminant detection, and the implementation of nanotechnology in smart medical devices [38]. Moreover, studying scientific collaboration networks will provide a deeper understanding of how research in nanotechnology and ethics is structured globally, fostering strategic partnerships between institutions. The integration of bibliometric tools and predictive models will help identify knowledge gaps and emerging areas with high-impact potential [39].In this context, future research must prioritize interdisciplinary approaches and transparent methodologies to enhance the understanding of the benefits and risks associated with nanotechnology [40]. These advances will contribute not only to technological development but also to the establishment of ethical governance frameworks that ensure its responsible application in society.

4. Conclusion

The bibliometric analysis of nanotechnology and ethics reveals significant growth in scientific production within this field over the past two decades. A review of publications indexed in Scopus between 2003 and 2025 shows a steady increase in research output, with an exponential rise in the number of published and cited documents. The predominance of scientific articles, accounting for 50.11% of total publications, suggests that researchers favor this format for presenting structured findings, while the presence of reviews at 16.55% reflects efforts to synthesize existing knowledge. In terms of impact, the *Journal of Nanotechnology and Ethics* stands out with the highest h-index of 22 and the largest number of accumulated citations, establishing itself as the leading source for specialized studies in nanoethics. Geographically, the United States and China lead scientific production in nanotechnology and ethics, followed by European countries such as the United Kingdom and Germany, underscoring the role of academic and governmental institutions in shaping this field. However, regions like Africa and Central Asia show lower participation, indicating potential opportunities for strategic collaborations and funding programs to foster research in these areas. Regarding scientific collaboration networks, Rodríguez J. and Williams K. are among the most influential authors with extensive international cooperation, highlighting strong connections between

researchers across different regions. These findings underscore the increasing relevance of nanotechnology and the necessity for clear regulations to ensure its ethical application. The study emphasizes the importance of continued exploration into the impact of nanomaterials in sectors such as biomedicine, sustainability, and agriculture, promoting responsible governance and transparency in the use of this technology.

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