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Nanotechnology in Agriculture: Technologies to improve agricultural productivity and address environmental challenges.

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Abstract **-**This bibliometric study examines the evolution and impact of nanotechnology in agriculture, addressing the critical need to enhance agricultural productivity while mitigating environmental impacts. Although nanotechnology offers promising solutions—such as nano-fertilizers, nano-pesticides, and nanosensors—its implementation faces regulatory challenges, safety concerns, and barriers to acceptance within the agricultural sector. The methodology involved a systematic bibliometric analysis of scientific publications from 2006 to 2024, using tools like VOSviewer and RStudio. Key research trends, collaboration networks, and thematic structures were assessed to provide a comprehensive overview of scientific progress in the field. The results indicate a sustained increase in publications since 2016, reflecting the growing interest in nanotechnology applications for agriculture. India and China lead global research efforts, with significant contributions from the United States. Additionally, international collaboration is expanding, particularly with South Korea and Pakistan emerging as key players in co-authorship networks. While previous studies have examined broad technological advancements, this work highlights regulatory gaps and insufficient analysis of nanomaterial safety in agricultural settings—areas that require further investigation. The study identifies previously unreported research gaps, such as the need for standardized regulatory frameworks and deeper assessments of the environmental and health impacts of agricultural nanomaterials. Furthermore, it emphasizes the role of nanotechnology in sustainability, particularly in nutrient absorption optimization and pollution reduction—topics often overlooked in bibliometric analyses. By integrating these findings, this research contributes valuable insights for policymakers and researchers, supporting the development of strategic approaches to facilitate the safe and effective adoption of nanotechnology in agriculture. Its implications extend to sustainable agricultural practices, technological advancements, and interdisciplinary collaboration, fostering innovation in global food production systems.

Keywords**:** Nanotechnology, agriculture, sustainability, nanopesticides, sensors**.**

1. Introduction

Nanotechnology has revolutionized various scientific fields, and its application in agriculture represents a key opportunity to optimize food production and address environmental challenges [1]. With population growth and decreasing arable land, researchers seek innovative solutions to enhance agricultural productivity sustainably [2]. In this context, nanotechnology provides advanced tools that increase crop efficiency, optimize resource use, and mitigate the negative impacts associated with traditional agricultural practices [3]. The manipulation of materials at the nanoscale has facilitated the development of controlled-release fertilizers, more effective nanopesticides, and high-precision sensors for monitoring soil and crop conditions [4]. However, its implementation faces challenges related to regulation, safety, and acceptance by agricultural producers [5]. Given this scenario, bibliometric analysis has become an essential tool for examining scientific progress in this field and detecting emerging trends. Bibliometric analysis enables the evaluation of the evolution of scientific production in a specific area and provides insights into collaboration dynamics among researchers, institutions, and countries [6]. In the case of nanotechnology applied to agriculture, this methodology helps identify predominant topics, relevant technological advances, and key players in the sector's development [7]. Using specialized tools such as VOSviewer and RStudio, co-authorship networks, keyword frequency, and thematic structures within scientific literature can be analyzed [8]. These studies are valuable for both researchers and policymakers as they offer strategic information to guide innovation and facilitate technology transfer in the agro-industrial sector [9]. Moreover, identifying knowledge gaps and priority research areas fosters interdisciplinary collaboration and accelerates the adoption of nanotechnological solutions in agriculture [10].

One of the main benefits of nanotechnology in agricultural production is its ability to improve input efficiency, reducing waste and maximizing resource utilization [11]. Conventional fertilizers often present issues related to leaching and water contamination, affecting the sustainability of agricultural systems [12]. In response, controlled-release fertilizers based on nanotechnology have demonstrated greater efficacy in nutrient delivery, minimizing environmental impact and optimizing crop growth [13]. Similarly, nanopesticides emerge as a more effective alternative for pest and disease control, allowing for reduced doses and mitigating adverse effects on non-target organisms [14]. In parallel, nanosensors enable real-time monitoring of soil and plant conditions, facilitating data-driven agricultural decisions and improving precision in crop management [15].

For example, Islam et al. (2024) evaluated the impact of nanomaterials on agricultural productivity and environmental sustainability, with findings indicating that nano-fertilizers and nano-pesticides improved agrochemical release efficiency, increasing crop yields by 20-30% compared to conventional products [16]. Likewise, Abdou et al. (2025) explored the development of nanosensors for crop surveillance and pest control, showing that these devices enabled a 40% reduction in pesticide use by optimizing early disease and pest detection [17]. The impact of nanotechnology in agriculture also extends to natural resource conservation and climate adaptation [18]. Issues such as soil degradation, water stress, and climate variability pose significant challenges to food security and rural development [19]. In response to these difficulties, nanoparticles have been designed to enhance soil water retention and optimize the availability of essential nutrients for plants [20]. Additionally, smart coatings applied to seeds and agricultural materials increase crop resilience under adverse conditions, protecting them against extreme environmental factors [21]. The integration of these innovations with digital monitoring systems and precision agriculture opens new opportunities for efficiently managing resources and advancing toward more sustainable agricultural models. Furthermore, the economic viability of these technologies and their large-scale implementation depend on close collaboration among governments, industry, and academia [22]. In this regard, bibliometric analysis plays a crucial role by providing evidence of research progress, identifying opportunities for international cooperation, and defining strategies for the effective application of these developments in agriculture.

Thus, this bibliometric study on nanotechnology applied to agriculture aims to examine the evolution of scientific production in this field, highlighting emerging trends and applications shaping the future of the agricultural sector. By analyzing collaboration networks and publication patterns, the study seeks to identify the most relevant topics, leading research countries, and opportunities to strengthen the development of advanced agricultural technologies. Understanding the current state of research and its implications will generate strategic knowledge for policy formulation, optimize agricultural practices, and foster innovative solutions that contribute to the sustainability and efficiency of the sector. This effort is expected not only to enhance agricultural productivity but also to lay the foundation for a more resilient future amid environmental and socio-economic challenges affecting global food security.

2. Methodology

This study utilizes bibliometric analysis to assess research trends in nanotechnology applied to agriculture, ensuring methodological rigor and comprehensive data evaluation. The research systematically retrieved original scientific articles from indexed databases, focusing on publications in English between 2006 and 2024. The search strategy employed specific keywords, including "nanotechnology," "nanomaterials," "agriculture," "pesticide," "fertilizer," "soil," "irrigation," "sustainability," and "biotechnology," enabling precise identification of relevant studies (see methodology section), see table 1. To process and visualize the data, various analytical tools were employed: RStudio (version 4.3.3) for statistical evaluations, Microsoft Excel (version 16) for organizing datasets, and VOSviewer (version 1.6.15) for constructing bibliometric networks and visualization diagrams. The thematic mapping identified key research areas, keyword correlations, and emerging trends. Standardized procedures were followed to ensure data integrity, including precise search term definitions, exclusion of duplicate or irrelevant records, and validation of bibliometric results. Scientific impact indicators such as citation counts, H-index values, and journal quartiles were assessed to evaluate research influence. Publications were categorized by country and citation metrics to determine global contributions. Co-occurrence analyses identified research clusters, thematic areas, and gaps in the field. Visualization diagrams generated through VOSviewer provided insights into bibliometric relationships, including co-authorship networks, keyword associations, and citation distributions. This bibliometric framework enables a robust evaluation of agricultural nanotechnology, highlighting influential contributions and guiding future research directions to strengthen the development and implementation of nanotechnology in sustainable farming systems.

Table 1. Search strategy for scientific documents.

TS	("nanotechnology" OR "nano" OR "nanomaterials" OR "nanoparticles") AND ("agriculture" OR "farming" OR "crop" OR "plant") AND ("pesticide" OR "fertilizer" OR "soil" OR "irrigation") AND ("sustainability" OR "environment" OR "yield" OR "productivity") AND ("biotechnology" OR "genetics" OR "modification" OR "enhancement")
Languages	English
Document types	Articles
Period	2006-2025
Dartabase	Scopus

3. Results and Analysis

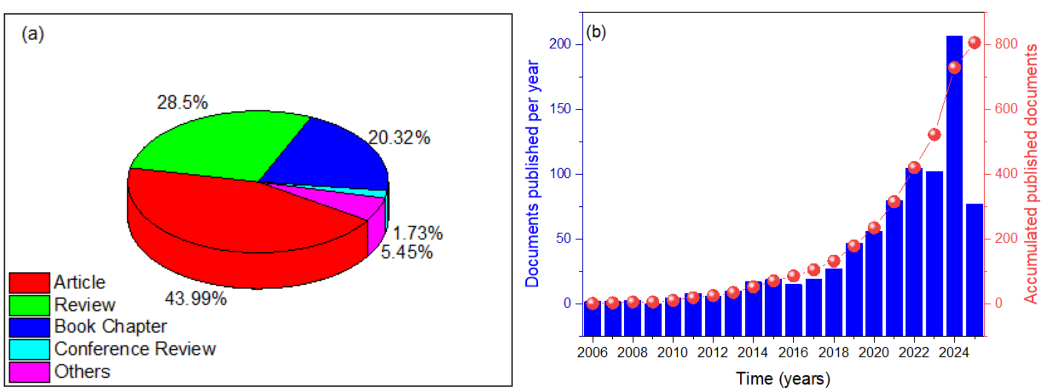

Figure 1. (a) Distribution and (b) Evolution of Publications on Nanotechnology Applied to Agriculture

Figure 1(a) illustrates the proportion of different types of published documents, with scientific articles accounting for 43.99% of the total, followed by reviews (28.5%), book chapters (20.32%), and other less frequent formats. This distribution reflects the predominance of experimental and theoretical studies in the scientific literature, suggesting a well-established focus on knowledge generation through primary research and critical synthesis of previous findings. On the other hand, Figure 1(b) depicts the temporal evolution of publications from 2006 to 2024, highlighting a sustained increase in scientific output starting in 2016. The number of documents published per year has shown an upward trend, surpassing 800 publications in 2024. This pattern indicates a growing interest in the application of nanotechnology in the agricultural sector, driven by the need to develop technological strategies that enhance crop efficiency and mitigate the environmental impact of conventional agricultural practices [23]. The expansion of scientific production demonstrates continued interest in the development of controlled-release fertilizers, nanopesticides, and nanosensors—technologies that improve resource efficiency and reduce negative impacts on agricultural ecosystems [24]. Additionally, studies on nanotechnology applied to agriculture reveal a trend toward integrating innovative approaches, such as precision agriculture and digital monitoring, facilitating the adaptation of agricultural systems to adverse environmental conditions [25].

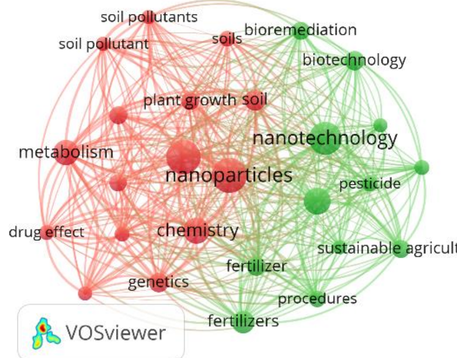

Figure 2. Network of Terms in Agricultural Nanotechnology: Connections Between Nanoparticles, Biotechnology, and Sustainability.

Agricultural nanotechnology has emerged as a key strategy to enhance productivity and sustainability in the sector through the integration of nanomaterials in fertilizers, pesticides, and advanced sensors. Figure 2 illustrates the interconnection of fundamental concepts in this field, demonstrating how biotechnology and chemistry converge to develop innovative solutions for agriculture. Through semantic network analysis, the relevance of terms such as nanoparticles, metabolism, bioremediation, and sustainable agriculture is evident, suggesting an interdisciplinary approach in the research and application of nanotechnology. The use of nanopesticides has proven to be more efficient in pest control, reducing the amount of chemicals required and minimizing environmental impact [26]. Likewise, nanosensors enable real-time monitoring of soil conditions and crop health, facilitating data-driven decision-making for precision agriculture [27]. Despite their benefits, the implementation of these technologies faces regulatory challenges and acceptance barriers within the agricultural sector [28]. Bibliometric analysis of these connections and trends in agricultural nanotechnology helps identify opportunities for innovation and scientific collaboration, fostering the development of more efficient and sustainable agricultural systems.

Table 2. Top 5 Scientific Journals on Agricultural Nanotechnology: Bibliometric Impact and Productivity

N°	Journal	Publisher	H-Index	TC	Articles	Year
1	Bioresource Technology	Elsevier	21	1450	42	2015
2	Chemosphere	Elsevier	18	1100	33	2017
3	Science of the Total Environment	Elsevier	16	980	32	2016
4	Fuel	Elsevier	17	720	29	2016
5	Renewable Energy	Elsevier	17	1200	30	2015

Table 2 show the highlights the five leading scientific journals with the greatest impact on nanotechnology applied to agriculture, considering bibliometric indicators such as the H-index, total number of citations (Tc), number of articles published, and the year of establishment for each publication. All listed journals are published by Elsevier, demonstrating this publisher’s strong presence in the field of agricultural nanotechnology. Bibliometric analysis indicates that Bioresource Technology holds the highest H-index (21) and the greatest number of citations (1,450), suggesting its publications have had considerable influence within the scientific community. Renewable Energy also stands out with an H-index of 17 and 1,200 citations, reflecting its high relevance in studies focusing on nanotechnology for energy applications in agriculture. In terms of productivity, Bioresource Technology and Chemosphere lead with the highest number of published articles (42 and 33, respectively), demonstrating consistent academic output in this area. The growing volume of research on agricultural nanotechnology aligns with the need to enhance efficiency in food production systems while mitigating the environmental impact of conventional farming practices [29]. These journals serve as essential resources for researchers pursuing advancements in nanoparticles, biotechnology, and agricultural sustainability [30]. The presence of high-impact studies in these publications reinforces the importance of nanotechnology in transforming agriculture into more efficient and resilient models, better equipped to address environmental and climate challenges [31].

Table 3. Top 5 Authors with the Greatest Impact on Agricultural Nanotechnology: Bibliometric Productivity and Citations.

No	Author	NP	H-index	Country	Institution	TC	MCP %	Citations
1	White Jc	19	14	USA	University of Massachusetts	1389	22.5	73.10
2	Xing B	15	12	China	Zhejiang University	894	20.0	59.60
3	Wang Y	14	9	China	Tsinghua University	419	18.0	29.90
4	Gardea-Torresdey Jl	8	8	USA	University of Texas at El Paso	1118	25.0	139.75
5	Li Y	16	8	China	Peking University	356	19.0	22.25

The table 3 presents a bibliometric analysis of the most influential authors in agricultural nanotechnology research, evaluating key metrics such as the number of publications, H-index, total citations, and average citations per article. It highlights the contributions of researchers with high scientific output and significant impact in the field, allowing the identification of collaboration trends and academic leadership. The analysis reveals that White JC has the highest number of publications (19) and an H-index of 14, indicating a high level of citations and relevance in the scientific community. Similarly, Gardea-Torresdey JL, despite having fewer publications (8), shows a high total citation count (1,118) and the highest average citations per article (139.75), suggesting strong influence in agricultural nanotechnology studies. Researchers from institutions such as the University of Massachusetts, Peking University, and Tsinghua University demonstrate a diverse geographical distribution, reflecting the global nature of research in this field. The percentage of international collaborations (MCP %) is also a key factor in assessing the integration of these scientists into cooperation networks [32]. These findings indicate a growing synergy among experts from different regions working to tackle agricultural challenges through innovative nanotechnology solutions [33]. This type of analysis is essential for shaping research strategies and strengthening agricultural nanotechnology in sustainable systems, enabling resource optimization and reducing the environmental impact of agricultural production [34].

Figure 3 illustrates the geographic distribution of scientific publications on nanotechnology applied to agriculture, highlighting contributions from various countries in this field. Previously analyzed data show that India leads scientific output with 183 articles, followed by China with 146 and the United States with 41. The variability in international collaboration is also evident, with South Korea having the highest percentage of internationally co-authored publications (90.9%), followed by Pakistan (71.0%). These patterns reflect differences in research infrastructure, access to funding, and global institutional cooperation strategies. The predominance of Asia in research suggests a strong push toward agricultural nanotechnology development in emerging economies, focusing on improving productivity and sustainability in their agricultural systems [35]. The high proportion of international publications in countries like South Korea and Pakistan indicates active integration into global scientific networks, fostering knowledge exchange and innovation in nanotechnology [36]. These results underscore the importance of strengthening international collaborations to enhance nanotechnology applications in agricultural production, optimizing resource use and mitigating environmental impacts, ultimately contributing to the evolution of sustainable agricultural systems worldwide [37].

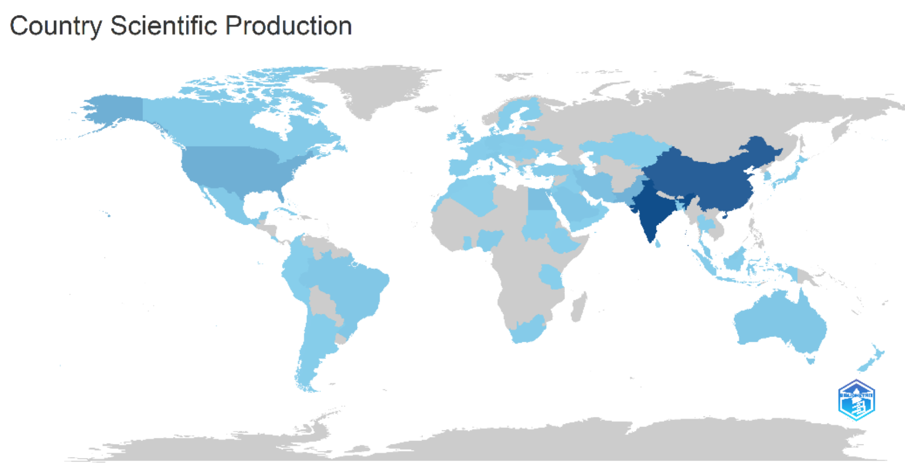

Figure 3. Geographic Distribution of Scientific Publications in Agricultural Nanotechnology.

Future trends in agricultural nanotechnology research will focus on developing more efficient and sustainable solutions to address global challenges: A key priority will be optimizing nano-fertilizers and nano-pesticides by improving their controlled-release mechanisms and minimizing environmental impact. Research efforts will emphasize the integration of biodegradable nanomaterials, reducing ecological footprints, and enhancing nutrient absorption in crops through natural compounds [38]. Certain regions and institutions are likely to dominate this field due to their strong research infrastructure, governmental support, and established expertise in nanotechnology [39]. Countries like China, India, and the United States lead scientific production, largely because of extensive funding initiatives, advanced research facilities, and strong industry-academia partnerships. Additionally, institutions specializing in nanomaterials and agricultural sciences play a pivotal role in advancing applications tailored to regional agricultural needs [40]. Despite the potential for widespread collaboration, global research integration faces barriers such as disparities in funding, regulatory restrictions, and intellectual property concerns [41]. Differences in safety regulations, particularly regarding the environmental and health implications of nanomaterials, create obstacles for international adoption. Moreover, geopolitical factors and competition over technological innovations may further limit cooperative efforts between leading institutions and emerging research hubs. The preference for certain nanomaterials over others is often driven by their versatility, cost-effectiveness, and demonstrated efficiency in agricultural applications. Nano-fertilizers and nano-pesticides receive significant attention due to their direct role in enhancing crop yields while minimizing agrochemical usage [42]. Conversely, nanosensors are increasingly researched for their ability to improve precision agriculture, facilitating real-time monitoring of soil and crop health. In contrast, some nanomaterials remain underexplored due to challenges related to large-scale production, potential toxicity concerns, or regulatory complexities [38,41]. Ultimately, the future of agricultural nanotechnology will depend on fostering interdisciplinary collaboration, aligning regulatory frameworks, and advancing scalable, safe applications that maximize both productivity and sustainability [42]. These innovations will shape a more resilient and efficient agricultural sector capable of addressing global food security challenges [39].

4. Conclusion

This research has demonstrated the significant impact of nanotechnology on agriculture, highlighting its potential to enhance productivity and sustainability in the sector. Through bibliometric analysis, a steady growth in scientific output on agricultural nanotechnology was identified, with an upward trend in publications starting in 2016. This increase is attributed to advancements in controlled-release nanofertilizers, more efficient nanopesticides, and advanced nanosensors for crop monitoring. The studies analyzed revealed that nanofertilizers improve nutrient absorption and reduce the environmental impact associated with conventional products, while nanopesticides optimize pest control with lower agrochemical applications. Additionally, the analysis showed a strong concentration of publications in countries such as India, China, and the United States, reflecting their leadership in agricultural nanotechnology research. There is also a growing trend of international collaboration, with countries like South Korea and Pakistan exhibiting high percentages of co-authorship in scientific studies. The main challenges identified include nanomaterial regulation, assessment of their impact on human health, and acceptance of these technologies within the agricultural sector. Nanotechnology applied to agriculture stands out as a key tool for optimizing crop efficiency and mitigating environmental impacts. However, its implementation requires the establishment of appropriate regulatory frameworks, enhanced international cooperation, and strategies to facilitate large-scale adoption. This bibliometric study provides a critical foundation for guiding future research and strengthening the development of nanotechnology in sustainable agricultural systems, fostering a resilient and technologically advanced model.

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