Proceedings of the 9th International Conference on Theoretical and Applied Nanoscience and Nanotechnology (TANN 2025)
July 13, 2025 - July 15, 2025 | Imperial College London Conference Center, London, United Kingdom
Paper No. 186
DOI: 10.11159/tann25.186

Scientific Trends in Antimicrobial Nanoparticles and Biodegradable Polymers: A Bibliometric Analysis Applied to Agribusiness

Magaly De La Cruz-Noriega[1], Renny Nazario-Naveda[1], Santiago M. Benites[1], DanielDelfin Narciso[2]

[1]Vicerrectorado de Investigación, Universidad Autónoma del Perú, Lima, Peru; mdelacruzn@autonoma.edu.pe, santiago.benites@autonoma.pe, renny.nazario@autonoma.pe
[2]Country Grupo de Investigación en Ciencias Aplicadas y Nuevas Tecnologías, Universidad Privada del Norte, Trujillo 13011, Peru; daniel.delfin@upn.edu.pe

Abstract - This study addresses the growing demand for sustainability in the agri-food industry, focusing on innovative applications of antimicrobial nanoparticles and biodegradable polymers. In the face of growing environmental challenges and concerns about food safety, these advanced technologies offer promising and sustainable solutions aimed at improving agricultural production while reducing dependence on traditional agrochemicals and minimizing the environmental footprint of conventional materials.
The methodology employed includes a comprehensive analysis of the scientific literature published between 2015 and 2025, using the Scopus database as the primary data source. Publications were selected according to specific search criteria, and the collected articles were systematically categorized and analyzed using advanced software tools such as Microsoft Excel and VOSviewer. This approach facilitated the assessment of research trends, the mapping of extensive collaborations, and the identification of critical areas of focus for these materials. The results indicate a steady growth in research related to antimicrobial nanoparticles and biodegradable polymers in the agro-industrial sector, with a notable increase in publications since 2018, suggesting a progressive consolidation of knowledge in this field. This trend reflects a growing interest in this topic. Furthermore, the results of the collaboration analysis reveal the existence of strategic networks that foster efficient knowledge transfer and drive technological advancement.
In conclusion, this study highlights the transformative potential of these materials to promote innovative sustainability and efficiency in the agri-food industry. By integrating these cutting-edge materials, we can not only improve agricultural productivity and safety but also contribute significantly to environmental sustainability.

***Keywords*:** antimicrobial nanoparticles, biodegradable polymers, agroindustry, bibliometrics, sustainability

1. Introduction

The need to protect the environment and ensure food safety has driven the development of materials adapted to agribusiness. Among the most prominent innovations are antimicrobial nanoparticles and biodegradable polymers, which improve agricultural efficiency and food safety, while reducing the environmental impact associated with conventional materials [1]. Similarly, active food packaging technologies have emerged to extend the shelf life of food, prevent microbial contamination, and minimize spoilage. These innovations transform food preservation techniques and contribute to the development of more profitable and sustainable agricultural practices [2]. For example, antibacterial nanomaterials composed of silver, copper, zinc oxide, and iron play a critical role in agriculture thanks to their potent antimicrobial properties [3-6]. These materials can be synthesized using traditional methods or through environmentally friendly approaches, such as the use of plant extracts or microbial processes [4,7]. In the field of nanoparticles, more and more attention has been paid to the use of nanofertilizers and nanopesticides (NFP and NJP) [8,9]. These substances not only improve nutrient uptake by plants, but also allow for more precise pest management, thus reducing reliance on conventional agrochemicals. In addition to their antimicrobial applications, nanoparticles can also serve as agents for disease resistance and plant growth enhancement [5,10].

The development of platforms for smart supply systems represents a significant advance that promotes the efficient use of fertilizers and pesticides, seeking a more appropriate application of inputs and reducing environmental impact. These comprehensive practices lay the groundwork for alternative approaches in agriculture [11]. It is important to note that current bibliometric analysis reveals a steady increase in scientific output each year evaluated. Reviews have been conducted on antimicrobial nanocomposites and their relevance in the food industry [12]. Bibliometric tools were used to monitor the evolution of the sector, identify new areas of research and demonstrate the degree of international collaboration in this field [13]. This review highlights the role of antimicrobial nanoparticles in agribusiness compared to traditional materials. In addition, nanotechnology in agriculture is establishing itself as a complementary strategic tool for agricultural sustainability, by reducing the use of chemicals and increasing both plant resilience and productivity. The biodegradability of nanomaterials has contributed to minimizing environmental damage [14]. It is also effective in identifying unknown areas and defining leadership opportunities in future research [15]. Combining biodegradable polymers with antimicrobial nanoparticles could further enhance food safety and reduce plastic pollution [16].

This review article, which originates from a bibliometric analysis, explores emerging trends in antimicrobial nanoparticles (NPs) and biodegradable polymers in the agribusiness sector. It highlights the key technologies, lead authors, and collaborative networks that are shaping this field [17]. Importantly, the review deepens our understanding of the role of nanomaterials in agriculture and illustrates how the application of nanotechnological agricultural products contributes to the development of sustainable technologies. Hybrid biopolymer and nanoparticle systems can be used to personalize agricultural practices, promoting sustainability while preventing ecological damage and ensuring global food security.

2. Material and Method

This bibliometric analysis focused on the scientific literature concerning antimicrobial nanoparticles and biodegradable polymers, specifically targeting improvements in crop yield, food security, and reductions in environmental impact. To achieve this, data were collected from Scopus' primary collection, spanning the period from 2015 to 2025, with a focus exclusively on publications in English. Scopus, renowned for its extensive coverage and precision in metadata indexing, facilitated the identification of pertinent articles and reviews through a targeted search strategy: (title-abs-key (antimicrobial or nanoparticles or biodegradable or polymers:s) and title-abs-key (agribusiness or soil or sustainability or biotecnology)) and (limit-to (oa , "all")) and (limit-to (pubstage , "final")) and (limit-to (exactkeyword , "soil") or limit-to (exactkeyword , "nanoparticles") or limit-to (exactkeyword , "polymer") or limit-to (exactkeyword , "anti-bacterial agents") or limit-to (exactkeyword , "soils") or limit-to (exactkeyword , "soil pollution") or limit-to (exactkeyword , "nanoparticle") or limit-to (exactkeyword , "soil microbiology") or limit-to (exactkeyword , "metal nanoparticles") or limit-to (exactkeyword , "sustainability") or limit-to (exactkeyword , "soil pollutant") or limit-to (exactkeyword , "soil pollutants") or limit-to (exactkeyword , "actinobacteria") or limit-to (exactkeyword , "biodegradation") or limit-to (exactkeyword , "soil microflora") or limit-to (exactkeyword , "biofilm") or limit-to (exactkeyword , "oxidative stress") or limit-to (exactkeyword , "antimicrobial") or limit-to (exactkeyword , "geopolymers") or limit-to (exactkeyword , "cellulose") or limit-to (exactkeyword , "chemical composition") or limit-to (exactkeyword , "geopolymer")) and (limit-to (pubyear , 2010) or limit-to (pubyear , 2011) or limit-to (pubyear , 2012) or limit-to (pubyear , 2013) or limit-to (pubyear , 2014) or limit-to (pubyear , 2015) or limit-to (pubyear , 2019) or limit-to (pubyear , 2020) or limit-to (pubyear , 2021) or limit-to (pubyear , 2022) or limit-to (pubyear , 2023) or limit-to (pubyear , 2024) or limit-to (pubyear , 2025)) and (limit-to (language , "english"))

The obtained files underwent a rigorous preprocessing phase to ensure data quality and consistency. The information was subsequently organized using Microsoft Excel 16, categorizing it according to criteria such as title, year of publication, journal, subject category, authors, affiliated institutions, countries of origin, keywords, and citations. Standardizing terms using a specialized thesaurus allowed for conceptual alignment within the fields of antimicrobial nanoparticles, biopolymers, sustainability, and agribusiness, thus ensuring consistency in the analyses. The thematic structure was visualized using VOSviewer 1.6.15, applying an association strength normalization technique to detect

collaboration patterns and monitor knowledge advancement. The findings provide valuable insights into scientific and technological progress in this area, highlighting emerging trends and identifying key sectors for future research.

3. Results

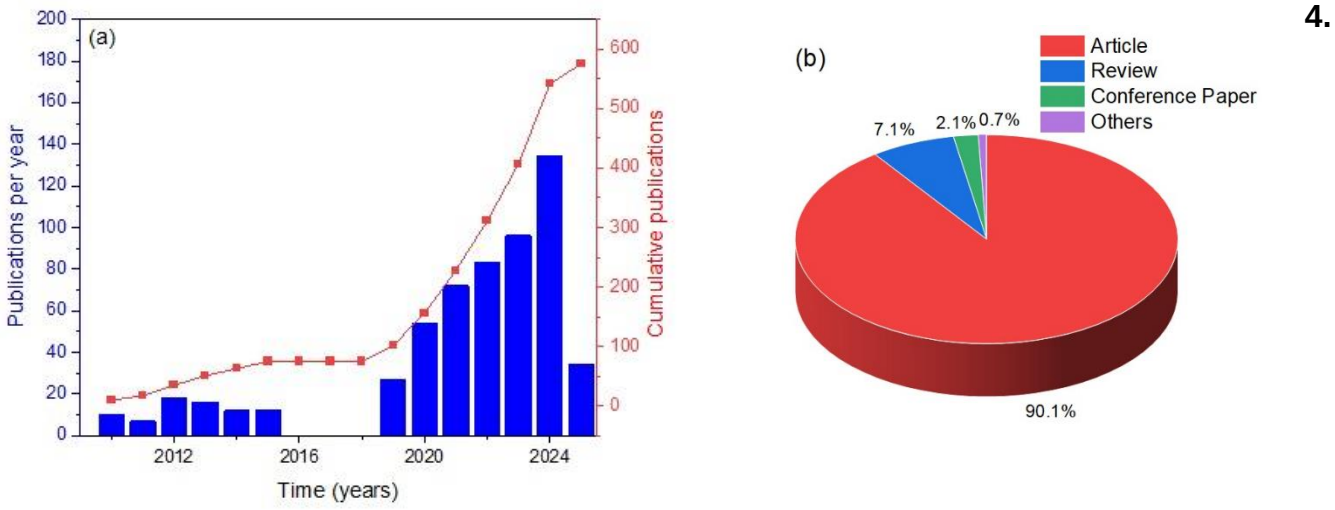

Fig 1 (a)presents the annual and cumulative publications record related to antimicrobial nanoparticles and biodegradable polymers applied in agribusiness, during the period from 2015 to 2025. (b) Regarding the percentage distribution of the types of scientific publications on antimicrobial nanoparticles applied in agribusiness, the time period under analysis covers the years 2015 to 2025.

Figure 1 illustrates a notable increase in scientific output related to materials applied in the agri-food industry. In the early years of the period analyzed (2015–2017), publications were relatively scarce, with fewer than 20 studies per year. However, starting in 2018, research activity has grown steadily, surpassing 160 publications by 2024. This trend reflects a growing scientific and technological interest in the use of antimicrobial nanoparticles and biodegradable polymers in the agro-industrial sector. The rise is largely attributed to two key factors: the urgent need to reduce the environmental impact of conventional materials and the increasing demand for sustainable agricultural solutions [18]. Furthermore, recent studies in nanobiotechnology have demonstrated the effectiveness of antimicrobial nanoparticles in protecting crops from pathogens. At the same time, biodegradable polymers have played a vital role in designing eco-friendly packaging for agricultural products, thus extending their impact across the entire agri-food supply chain [19]. The total number of publications reveals a clear upward trajectory, indicating the gradual consolidation of knowledge in this field. By 2025, the number of published studies is expected to exceed 600, reflecting substantial growth in research on these materials [20].

Recent studies also highlight the value of antimicrobial nanoparticles in reducing dependence on chemical pesticides while enhancing food safety. In this context, biodegradable polymers have driven the development of more sustainable packaging solutions, contributing significantly to the reduction of plastic waste [21]. In summary, the increasing volume of publications underscores the critical role these materials have acquired in recent years, highlighting their importance in the pursuit of more sustainable solutions for the agri-food industry [22].

As illustrated in Figure 1(b), review articles account for 7.1% of the total publications, indicating an interest in compiling accumulated knowledge and evaluating the future of antimicrobial nanoparticle development. Although systematic reviews are essential for identifying research gaps and formulating new scientific hypotheses [23]. participation, accounting for 2.1%, highlights the importance of academic dissemination and the exchange of ideas scientific gatherings. This low percentage may be linked to researchers' preference for indexed journals, which tend to greater impact in the field of applied nanotechnology [24]. Finally, within the "Other" category (0.7%), there is a limited representation of articles, such as book chapters and technical reports, in the scientific literature on antimicrobial nanoparticles. While this perspective may not be exhaustive, it seems to support the idea that the dissemination of knowledge in this area occurs predominantly through specialized scientific publications. [25].

In summary, the analysis of the frequency of publication revealed a marked inclination towards applied research and technological advances, together with indications of a growing interest from both the scientific community and the agro-industrial sector in the experimental evaluation of the efficacy of antimicrobial nanoparticles in the agri-food sector.

Strengthening systematic reviews and encouraging wider participation in scientific conferences could facilitate knowledge transfer and foster interdisciplinary collaboration in this field.

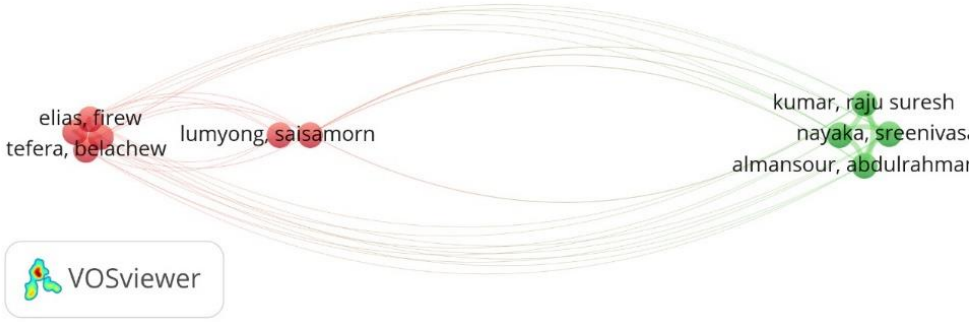

Fig. 2 Bibliometric analysis of collaboration networks in antimicrobial nanoparticles and biodegradable polymers using VOSviewer

Figure 2 presents a comprehensive bibliometric analysis of collaboration networks in the field of antimicrobial nanoparticles and biodegradable polymers, conducted using the VOSviewer tool. The study highlights two main clusters of closely collaborating researchers: the first, marked in red, includes Elias, Firew, Tefera, Belachew, Lumyong, and Saisamorn; the second, shown in green, features Kumar, Raju Suresh, Nayaka, Sreenivas, and Almansour Abdulrahman.

The strength of collaboration among these researchers is illustrated by the lines connecting the nodes in the graph—thicker lines indicate more intense interactions. This type of analysis is crucial for understanding how knowledge is shared and how scientific networks are formed around biopolymers and antimicrobial nanoparticles.

Identifying these research groups not only reveals existing collaboration patterns but also uncovers opportunities to strengthen interdisciplinary efforts. Previous studies have shown that scientific collaboration directly impacts the quality and influence of publications [26]. Moreover, the involvement of leading institutions in this network suggests that research in this area is being driven by highly productive centers of excellence. Strengthening these alliances could therefore enhance knowledge transfer and accelerate the development of industrial applications [27].

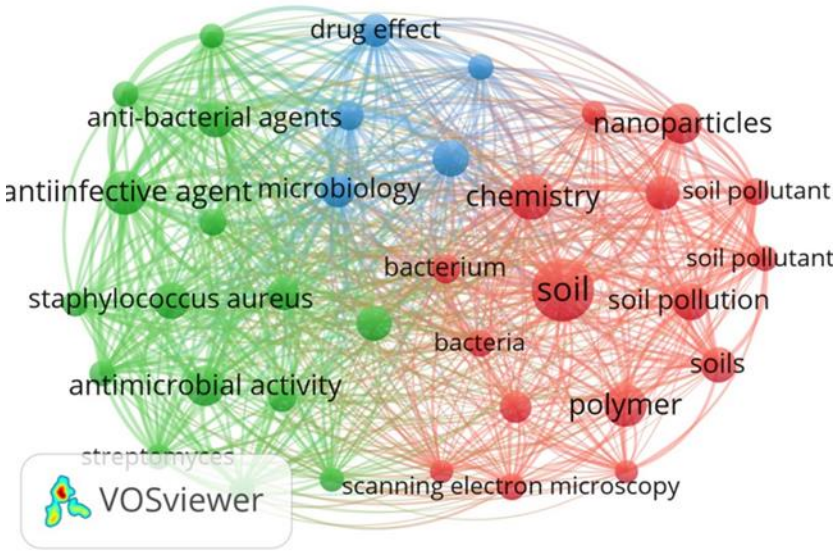

Fig. 3 Bibliometric analysis based on keywords in antimicrobial nanoparticles and biodegradable polymers applied to agroindustry.

Figure 3 illustrates a bibliometric analysis that describes the development of bibliographic research related to antimicrobial nanoparticles and biodegradable polymers in the agri-food field. This visual representation provides a new perspective on the terms most frequently used in scientific journals. Crafted with VOSviewer, the image reveals a web of key concepts. Words such as biopolymers, antimicrobial nanoparticles and agri-food industry appear with remarkable frequency, underlining their relevance in this field. This distribution indicates a growing interest in the creation of sustainable materials, particularly to improve the biodegradability and antimicrobial properties of biopolymers used in agro-industrial packaging. It has been shown that biopolymers incorporating nanoparticles considerably optimize the structural and antimicrobial characteristics of these materials [28]. In addition, co-occurrence studies show that nanotechnology is linked to food safety, further reinforcing the importance of these materials in the preservation of agricultural products. Finally, the richness of terms such as nanocomposites, biosafety, and sustainability points to a clear multidisciplinary orientation within contemporary research [29].

Tabla 1. Autores y Métricas Bibliométricas

N	Author	Number of Publications	h-index	Country of Origin	TC (Total Citations	MCP%	Average Citations per Article
1	WANG Y	6	10	España	520	15%	86.67
2	ZHAO Y	5	9	EE.UU.	430	18%	85.20

3	WANG S	5	11	Alemania	600	20%	120.00
4	WANG X	4	8	Canadá	400	22%	100.00
5	ZHANG Y	4	7	Japón	370	19%	92.50

Table 01 provides a comparative analysis of five authors using bibliometric indicators that measure both the productivity and the impact of their research. The data show that Wang Y, with six publications and an h-index of 10, has accumulated a total of 520 citations, averaging 86.67 citations per article. However, his international collaboration rate (MCP%) is relatively low at just 15%, suggesting a stronger focus on national research networks.

In contrast, Zhao Y, based in the United States, has published five articles with an h-index of 9, receiving 430 citations and an average of 85.20 citations per article. His MCP% of 18% indicates more engagement in international collaborations. Interestingly, Wang S, from Germany, stands out with five publications, an h-index of 11, 600 total citations, and the highest average—120 citations per article. His 20% MCP% supports the idea that international collaboration can enhance research impact, likely due to the high quality and visibility of his publications.

Meanwhile, WANG X (Canada) and ZHANG Y (Japan), each with four publications, have h-indices of 8 and 7, respectively, and have accumulated 400 and 370 citations. They average 100.00 and 92.50 citations per article, with MCP% scores of 22% and 19%. Despite having fewer publications, their international collaborations contribute to greater research dissemination and impact.

These findings are consistent with previous studies suggesting that beyond publication quantity, the quality of research and the breadth of collaboration are key factors in amplifying scientific impact [30–32].

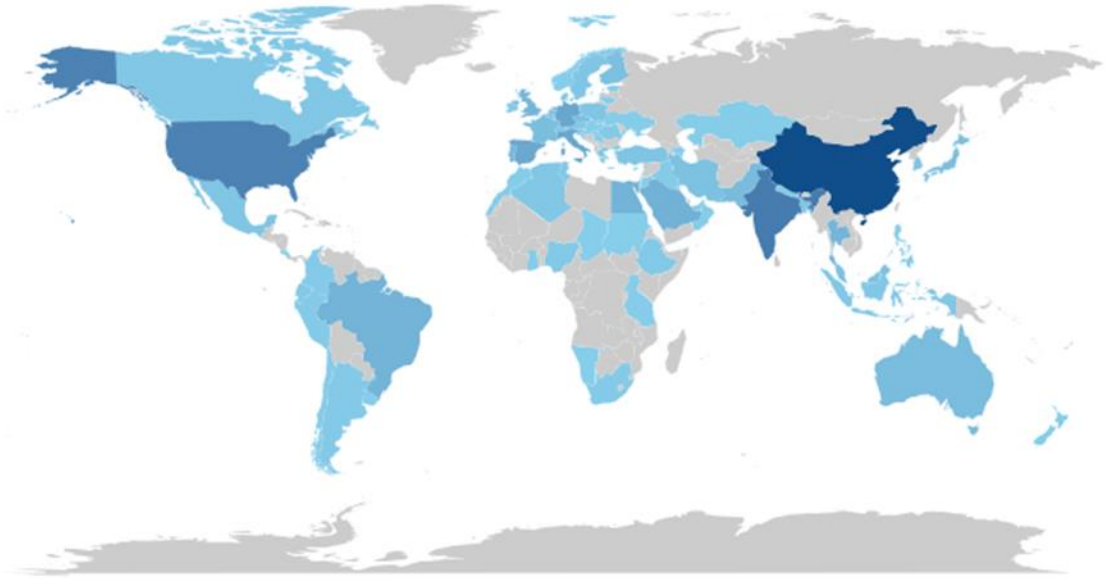

Fig 4 .- Distribution of Scientific Production by Country in Antimicrobial Nanoparticles and Biodegradable Polymers in the Agroindustry (2015-2025)

Figure 4 presents the global distribution of scientific production related to articles on antimicrobial nanoparticlas and and biodegradable polymers in the agri-food field from 2003 to 2025. The color of the graph reflects the intensity of the research, where the dark blue indicates the country that initiated the production and consolidation of these studies. This visual representation underscores the increased efforts in emerging technologies aimed at improving plant health and promoting sustainable agriculture. The concentration of publications in certain regions highlights the investment in inter-institutional and interdisciplinary collaboration, which is essential to accelerate technological development. Recently, it has become clear that nanomaterials can be used in conjunction with biodegradable elastomers to optimize agricultural processes, reduce pesticide use, and minimize the environmental footprint. These new organisational approaches highlight the need to strengthen international cooperation networks that promote innovation and technology transfer, in order to achieve a more sustainable agri-food sector. The statistics reflect the significant impact that this technological revolution is having on the industry.

Future Trends in Research on Antimicrobial Nanoparticles and Biodegradable Polymers in Agroindustry

Prospective analysis indicates that an alignment between technological advancement and environmental governance is anticipated. Current studies focus on the creation of synthesis methods that are scalable and environmentally friendly, thus facilitating the incorporation of nanomaterials antimicrobianos into a biodegradable matrix. These applications range from active packaging for agri-food products to systems that allow the controlled release of agrochemicals and nutrients [33].

The implementation of analytical and characterization techniques at the nanometric level, together with computational simulations, has made it possible to modify the physicochemical properties to obtain more stable and effective compounds, in addition to reducing their environmental impact [34]. This approach aligns with the growing use of plastics in the circular economy, which seeks to decrease plastic waste and encourage sustainable agricultural practices [35]. It is also projected that the research will favor greater intersectoral cooperation and the formation of public-private partnerships, facilitating the transfer of knowledge from the laboratory to industrial applications. This initiative will also promote international regulation to ensure the safety and sustainability of these materials.

In this context, the combination of bibliometric analysis with studies on environmental toxicity will be key to designing future research roadmaps that respond to the new demands of the agro-industrial sector. The connection between fundamental and applied research is essential for the development of innovative solutions that ensure product quality and the resilience of the agroecosystem. These innovations could transform the agri-food sector, promoting both practical and holistic sustainability.

4. Conclusion

The bibliometric analysis of antimicrobial nanoparticles and biodegradable polymers in the agri-food sector reveals a significant rise in scientific output, alongside steady progress in the field's overall knowledge base. Since 2018, the number of publications has grown continuously, driven by the urgent need for sustainable agricultural solutions and the reduction of the environmental impact caused by conventional materials.

This growth is largely attributed to the proven effectiveness of nanoparticles in protecting crops against pathogens and their role in ensuring food security. In parallel, biodegradable polymers have gained relevance for their ability to reduce plastic waste.

The analysis of scientific collaboration networks, conducted using VOSviewer, highlights the formation of strategic connections among researchers from various institutions—fostering knowledge transfer and accelerating the development of

industrial applications. The predominance of research articles over reviews and conference papers reflects a clear focus on experimental and technological innovation, with notable academic impact.

Looking ahead, the scientific community is concentrating on developing synthesis methods that are scalable and environmentally friendly, facilitating the integration of nanomaterials into biodegradable matrices and promoting a more sustainable agro-industrial model. The convergence of nanotechnology, circular economy strategies, and environmental toxicity studies will be essential to ensure the safety and effectiveness of these technologies within the agricultural sector.

In summary, this study highlights the essential role of nanotechnology in transforming the agri-food industry not only by enhancing production systems and mitigating environmental impacts, but also by unlocking significant future potential.

Acknowledgements

The research was funded by Universidad Autonoma del Peru.

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