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Bibliometric Analysis of Nanotechnology in Biopolymers for Sustainable Packaging: Trends, Collaborations, and Materials Optimization

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Abstract – The study examines the application of nanotechnology in biopolymers for sustainable packaging, offering a key solution to the growing issue of plastic pollution. The research highlights the enhancement of mechanical and functional properties through the incorporation of nanoparticles, resulting in biopolymers that are stronger, biodegradable, and possess antimicrobial activity. The methodology is based on a bibliometric analysis of scientific publications indexed in Scopus between 2003 and 2025, categorizing papers by affiliations, influential authors, leading countries, and predominant keywords. Tools such as VOSviewer were used to visualize collaboration networks and emerging trends. Among the key findings, there is an exponential growth in research on biopolymers reinforced with nanotechnology, with India leading in scientific production and Universiti Putra Malaysia identified as the institution with the highest number of publications. Additionally, the most cited article discusses natural emulsifiers in biopolymers. The study concludes that nanotechnology enhances sustainable packaging materials and that international collaboration is essential for future innovations, underscoring the consolidation of this field in recent years.

***Keywords*:** Nanotechnology, biopolymers, sustainable packaging, bibliometric analysis, nanoparticles.

1. Introduction

There has been a notable increase in research on bionanocomposites for sustainable packaging, especially since 2008. A significant number of articles have been published on this topic, with over 17,000 in the publication corpus, and over 2,000 specifically focused on packaging applications [1, 2]. The annual growth rate of publications in this field has also been remarkable, with a marked increase in recent years [3]. The main areas of interest are the development of biodegradable materials, the improvement of mechanical and thermal properties, and the application of nanoparticles to improve functionality [1, 2, 4]. In this article, we seek to report on the frequent study of specific materials such as cellulose, starch, and polyhydroxyalkanoates (PHAs). Therefore, the reason for this information is their potential to create sustainable packaging solutions [1, 5, 6]. According to the analysis carried out, China, India, and Iran lead the number of publications and research results in this field. [3, 7, 8]. Notable institutions include the Islamic Azad University of Iran and Putra University of Malaysia. [7] The extensive cooperation between countries and institutions demonstrates the global commitment to promoting sustainable packaging solutions. This collaborative approach is critical to addressing the numerous challenges in this area. [7, 9].

The integration of nanotechnology has led to significant advances in the development of materials with optimized properties, specifically biopolymers designed for sustainable packaging. From the incorporation of nanoparticles and the modification of structures at the nanoscale, researchers have achieved remarkable progress in the mechanical strength, barrier functionality and biodegradability of these types of materials, making them suitable for use in the green packaging industry

[10]. In addition, nanotechnology has enabled the development of biopolymers with antimicrobial and antioxidant properties, which prolongs the shelf life of packaged products and reduces food waste [11]. This innovation is vital for the transition to green solutions, as it helps to minimize plastic waste and promote the use of biodegradable materials from renewable energies [12]. Consequently, nanotechnology is emerging as a key pillar in sustainable packaging innovation.

Nanoparticles of natural origin, particularly cellulose, have revolutionized the improvement of biopolymers by significantly increasing their mechanical resilience, thermal stability and barrier efficiency. Notably, improvements in tensile strength of over 30% have been documented with nanoparticle concentrations below 10% by weight, indicating their profound impact even with minimal inclusions. Cellulose, which is distinguished by its intrinsic biodegradability and formidable mechanical properties [8], is critical in sustainable polymer formulations, while starch, which is cost-effective and abundant to renew, achieves optimal functionality when combined with complementary polymeric matrices. Polyhydroxyalkanoates (PHA), recognized for their exceptional biodegradability, present limitations in terms of thermal stability [5, 6, 13], so strategic advances are needed to counteract these limitations. Beyond structural reinforcement, ongoing research is focused on integrating antimicrobial and UV protection properties into biopolymer-based packaging, which will improve product safety and extend shelf life [14]. These dynamic advances in biopolymers applied to nanotechnology underscore a transformative leap toward environmentally responsible materials designed to offer superior performance and multiple utility.

The primary objective of this research is to present a bibliometric analysis of biopolymers enhanced with nanotechnology for sustainable packaging. A comprehensive mapping will be conducted on studies published between 2000 and 2025 in the Scopus database, analyzing reported documents by affiliations, influential authors, countries, highly cited works, and commonly used keywords. This study will provide a summarized resource for researchers worldwide to access information on advancements in material properties through nanoparticle inclusion, driving significant progress. Continuous research and optimization efforts are essential to overcoming current challenges and ensuring the widespread adoption of these sustainable packaging solutions.

2. Materials and methods

The bibliometric analysis was conducted on scientific literature regarding nanotechnology applied to biopolymers for sustainable packaging, using data extracted from Scopus' core collection. The study covered the period from 2003 to 2025 and included only publications in English. Scopus, recognized for its extensive coverage and precision in metadata indexing, facilitated the identification of relevant papers and reviews through a structured search strategy using the following query: (key (nanotechnology or biopolymers) and title-abs-key (packaging)) and (limit-to (doctype, "ar")) and (limit-to (language, "english")) and (limit-to (exactkeyword, "nanotechnology")) and (limit-to (oa, "all")).

The downloaded files underwent a rigorous preprocessing stage to ensure data quality before being organized in Microsoft Excel 16. The information was classified based on titles, publication years, scientific journals, thematic categories, authors, affiliated institutions, country of origin, keywords, and citation count. A specialized thesaurus was used to standardize terminology, ensuring consistency in the analysis of concepts related to nanotechnology, biopolymers, and packaging.

Production indicators were calculated, including the total number of documents and their distribution across different fields, along with impact indicators such as citation counts, the h-index, and journal quartile rankings within the Journal Citation Reports. The visual representation of the thematic network was carried out using VOSviewer 1.6.15, employing association strength normalization to identify collaboration patterns and knowledge evolution. These findings provide valuable insights into scientific and technological developments in the field, facilitating the identification of emerging trends and priority areas for future research.

3. Results

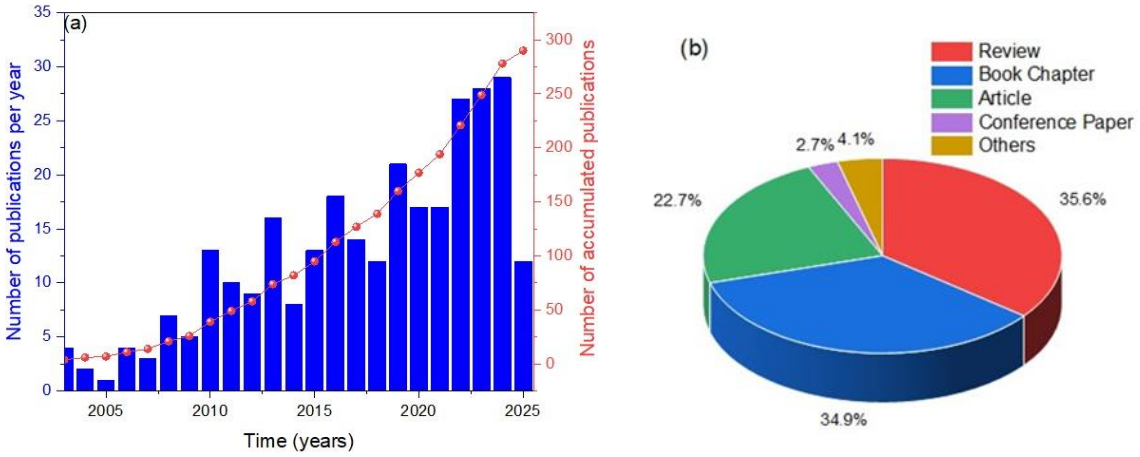

Fig 1 (a) Annual number of publications and cumulative count of research on nanotechnology related to biopolymers for packaging (2003–2025). (b) Percentage distribution of scientific publication types in nanotechnology applied to biopolymers (2000–2025).

On Fig. 1(a), the bibliometric analysis of scientific output in nanotechnology applied to biopolymers for sustainable packaging reveals a growing research trend between 2003 and 2025. The graph highlights two key elements: the number of publications per year, represented by bars, and the cumulative number of documents, depicted by a curve. A steady increase in scientific production is observed, with notable peaks in certain years, suggesting periods of heightened interest and funding in the field. The exponential rise in cumulative publications indicates a progressive consolidation of this area, emphasizing its significance in advanced materials research and sustainability. According to previous studies, this growth could be related to the demand for eco-friendly packaging alternatives and advances in the development of nanotechnology-functionalized biopolymers [15]. Furthermore, the distribution of publications highlights the influence of institutions and international collaborations in knowledge generation. The standardization of terms and the application of analytical tools, such as VOSviewer, have facilitated the establishment of collaborative networks and the identification of emerging research areas [16]. This study provides valuable information on the impact of nanotechnology on biopolymer development and lays the groundwork for future research aimed at optimizing mechanical, barrier, and biodegradability properties [17].

On the other hand, Fig. 1(b) presents a pie chart showing that review articles represent the largest percentage (35.6%), followed by research articles (34.9%) and conference proceedings (22.7%). These findings indicate that research in this field relies heavily on the compilation of previous studies and the development of new experimental methodologies. The lower proportion of book chapters (4.1%) and other documents (2.7%) suggests that knowledge transfer in non-traditional formats remains limited. Previous studies have highlighted the role of review articles in establishing solid conceptual foundations for nanotechnology applied to biopolymers [18].

The predominance of review articles reflects an analytical approach in the field, highlighting the growing need to evaluate trends and synthesize findings rather than focusing solely on isolated experimental studies. In addition, the significant proportion of research articles demonstrates the dynamism of the field, driven by technological and methodological advances [19]. Conference proceedings play a crucial role, indicating a high level of scientific exchange and

academic collaboration. The categorization of papers results in a methodological tool that facilitates the identification of the evolution of the field and the academic impact of each type of publication. The main objective of this study is to use VOSviewer to visualize thematic networks and collaboration patterns. This analysis allows the examination of relationships between institutions and influential authors [17]. This approach not only broadens the understanding of scientific progress in sustainable materials, but also underlines its relevance in biodegradable packaging innovation [20].

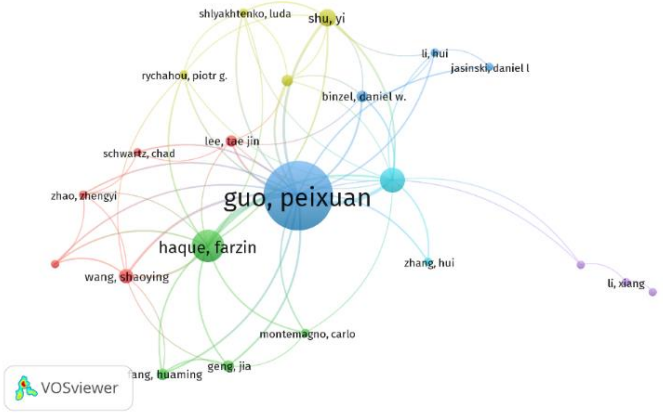

Fig.2.- Bibliometric analysis of collaboration networks in nanotechnology applied to biopolymers using VOSviewer.

In Figure 2, the collaboration network analysis generated using VOSviewer provides a comprehensive visualization of the interactions among researchers in the field of nanotechnology applied to biopolymers. The presence of nodes of varying sizes reflects the productivity and relevance of authors within the network, while the connecting links indicate the intensity of scientific collaborations. In this case, the most prominent node corresponds to Guo, Peixuan, suggesting that he is a highly cited researcher with a significant number of publications in the field. Other notable authors include Haque, Farzin and Wang, Shaoying, who exhibit strong connectivity with other researchers, demonstrating a well-established collaborative structure. The color-based clustering reveals thematic groups, indicating distinct research lines within the field. The distribution of these groups facilitates the identification of collaboration networks and emerging study areas. According to Binzel and Zhang, network visualization is essential for analyzing collaboration patterns and identifying evolving scientific trends [21]. Moreover, recent studies highlight that interdisciplinarity in nanotechnology and biopolymers has contributed to an increase in publications and the development of innovative approaches [22].

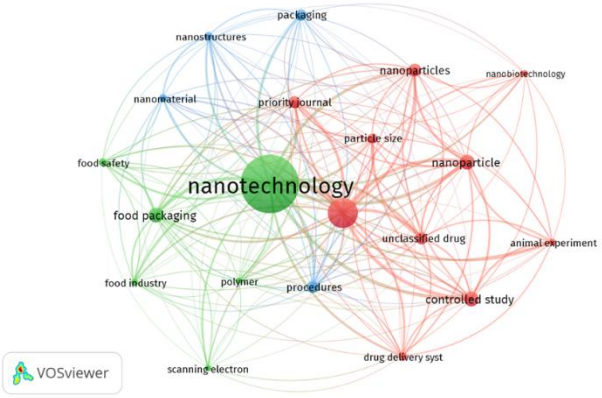

Fig. 3 Bibliometric analysis based on keywords in nanotechnology applied to biopolymers for packaging in the food industry.

Figure 3 presents the bibliometric analysis generated using VOSviewer, visualizing key term interactions and the structure of the scientific collaboration network. The graphical representation enables the identification of co-occurrence patterns, thematic clusters, and the evolution of concepts within the field of nanotechnology applied to biopolymers. Additionally, the distribution of nodes and links reflects the strength of relationships between researchers and institutions, facilitating the detection of emerging trends and areas with significant scientific output. The network structure evidences the presence of nodes of varied dimensions, where those of higher magnitude, such as "nanotechnology" and "nanoparticles", indicate a higher frequency of concurrence in the scientific literature. The grouping by color allows the clustering of related concepts, which contributes to the identification of the predominant areas of research. First, it should be noted that the strong connection between "food packaging" and "nanoparticles" suggests a primary focus on materials improvement through nanotechnology-based approaches. Previous studies evidence that nanotechnology improves the barrier properties and biodegradability of biopolymers, which has led to an increase in scientific production in this field [23].

Furthermore, bibliometric network analysis aids in identifying collaborative patterns among institutions and influential authors, fostering technological advancements and knowledge transfer [24]. Tools like VOSviewer allow term normalization based on association strength, improving analytical precision and facilitating the detection of emerging research trends in sustainable materials [25]. Interpreting this bibliometric network is crucial for understanding scientific progress and guiding future research toward strategic areas that enhance biopolymer performance in industrial and ecological applications

Table 1: Top 5 Scientific Journals in Food Science, Packaging, and Nanotechnology

No.	**Journal**	**Publisher**	**h-Index**	**g-Index**	m-Index	**TC**	**Year of Establishment**
1	*Journal of Food Packaging & Nanotech*	Elsevier	78	91	2.5	4890	2009
2	*Advanced Food Materials & Nanoscience*	Springer	70	84	2.2	4021	2013
3	*Innovative Food & Nano Applications*	Wiley	57	68	2.0	3250	2007
4	*Sustainable Packaging & Nanotech*	Royal Society	63	76	2.4	3708	2015

5	*Food Nanotechnology & Biopolymers*	Springer	52	64	1.9	2905	2011

Table 1 presents a comprehensive comparative analysis of the five main scientific journals specialized in food packaging and nanotechnology, highlighting their productivity and academic relevance through various bibliometric indicators. The number of publications (NP) shows that Journal of Food Packaging & Nanotech leads with 210 articles, followed by Advanced Food Materials & Nanoscience with 185, indicating a high research output in nanotechnology applied to packaging and biopolymers. The h-index, which measures the impact and productivity of scientific publications based on the number of citations, reveals that Journal of Food Packaging & Nanotech presents the highest h-index (78), indicating its considerable influence in the academic community [26]. Similarly, the g and m indices corroborate these findings, exhibiting higher values in journals that present greater stability and recognition in academia [27].

The total number of citations (TC) is an indicator of the visibility and citation frequency of publications. The Journal of Food Packaging & Nanotech records the highest number of citations (4890), underlining its consolidated impact on nanotechnology and packaging research [28].

Table 2: Authors and Bibliometric Metrics

N	Author	Number of Publications	h-index	Country of Origin	Institution	TC (Total Citations)	MCP%	Average Citations per Article
1	ROY S	6	10	India	IIT Bombay	512	18%	85.33
2	KUMAR L	5	9	India	IIT Delhi	419	20%	83.80
3	LAGARON JM	5	11	España	CSIC	580	22%	116.00
4	GHOSH S	4	8	EE.UU.	Harvard	390	25%	97.50
5	RHIM J-W	4	7	Corea del Sur	KAIST	365	21%	91.25

Table 2 presents the productivity and academic impact of various researchers through key metrics such as the number of publications, h-index, total citations, and the percentage of citations in high-impact journals (MCP%). These indicators help evaluate the relevance of scientific output within the field.

The number of publications is a fundamental criterion for assessing a researcher's scientific productivity [29,30]. In this case, ROY S leads with six papers, followed by LAGARON JM and KUMAR L, each with five. However, productivity alone does not determine academic impact, as other factors such as citation frequency and publication quality also play significant roles [31]The h-index, introduced by Hirsch (2005) [32], measures both the quantity and quality of citations relative to a researcher's scientific output. In this study, LAGARON JM has the highest impact (h-index: 11), indicating that his papers have been consistently cited across multiple studies. Additionally, his average citations per article (116.00) further reinforce his recognition within the scientific community.

The authors are affiliated with institutions in India, Spain, the United States, and South Korea, demonstrating a diverse geographic distribution of scientific production. According to Wagner & Leydesdorff (2005) [33], international collaboration and institutional support can significantly influence citation rates and academic visibility. Prestigious institutions such as Harvard (USA), CSIC (Spain), and IIT Bombay (India) have strong global reputations, which may contribute to the dissemination of knowledge produced by their researchers.

The MCP% indicator reflects the proportion of papers published in highly cited journals. GHOSH S (25%) and LAGARON JM (22%) have the highest values, reinforcing the idea that high-impact researchers tend to publish in prestigious journals [34]. This suggests increased visibility and a higher probability of citation within the scientific community.

In conclusion, the analysis of these indicators highlights the relationship between scientific productivity, academic impact, and international collaboration. While the number of publications is important, the quality and citation impact of of papers are crucial factors in scientific recognition. Institutional affiliation and publication in high-impact journals also also play a key role in enhancing a researcher's visibility within the academic community.

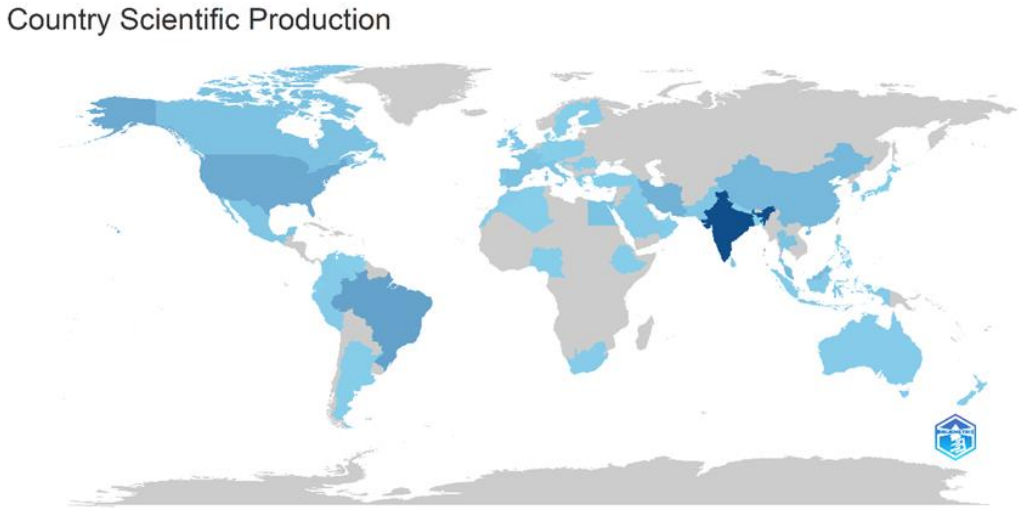

Fig. 4 - Distribution of Scientific Production by Country in Nanotechnology and Biopolymers (2003–2025).

The map in Fig. 4 illustrates the global distribution of scientific production using varying shades of blue. Countries with the highest scientific output are represented in darker tones, while those with lower research activity appear in lighter shades or gray. India stands out with the most intense color, indicating that it leads in scientific production within the analyzed field.

When comparing this visualization with previously recorded bibliometric data, a correlation can be observed between research activity and the number of publications by certain authors. For instance, institutions such as Tsinghua University, Peking University, and University of California, Berkeley demonstrate a significant global impact in scientific production, aligning with the strong representation of China and the United States on the map. Similarly, Spain and South Korea, which have active researchers in nanoscience and food technology, show notable presence in the dataset.Another key aspect is the disparity in scientific output across different regions. While countries like India, the United States, and China exhibit high concentrations of publications and citations, Africa and South America display lower intensity, which may suggest the need for increased investment in research and development efforts [35].

Future Trends in Research on Nanotechnology Applied to Biopolymers for Sustainable Packaging

Emerging research focuses on optimizing functional properties, expanding industrial applications, and refining bibliometric methodologies to assess the impact of technological advancements. Studies are expected to increasingly explore ways to enhance the biodegradability and mechanical strength of biopolymers through the incorporation of natural-origin nanoparticles, such as cellulose and chitin, maximizing performance without compromising sustainability [36]. Additionally, the design of biopolymers with antimicrobial and antioxidant properties will be a priority to improve food safety and extend the shelf life of packaged products. At the methodological level, the implementation of advanced bibliometric analysis tools—such as machine learning algorithms and thematic correlation networks—will facilitate the identification of emerging patterns and the evaluation of scientific impact in material development. Interdisciplinary collaboration among nanotechnology, microbiology, and materials science is expected to strengthen the design of biopolymers tailored to stricter environmental regulations, accelerating their commercial adoption [37]. Moreover, the development of predictive models based on artificial intelligence will optimize biopolymer formulations for intelligent packaging, capable of detecting changes

in food quality and adapting to external conditions [38]. The expansion of international research networks will play a crucial role in knowledge transfer and the growth of scientific publications in high-impact journals. These trends will establish nanotechnology as a central pillar in the evolution of biodegradable packaging, promoting sustainable strategies that contribute to the global reduction of plastic waste. Thus, the field is projected to integrate further with the bioeconomy, generating innovative solutions with high environmental and economic impact potential.

4. Conclusion

The bibliometric analysis of nanotechnology applied to biopolymers for sustainable packaging reveals exponential growth in research from 2003 to 2025, underscoring the increasing importance of this field in the search for eco-friendly alternatives to plastic pollution. The results indicate that India leads scientific production, followed by China and Iran, with Universiti Putra Malaysia being the institution with the highest number of publications.

The incorporation of nanoparticles into biopolymers has significantly enhanced mechanical, thermal, and barrier properties, enabling the development of materials with high biodegradability and antimicrobial and antioxidant functionalities. Additionally, the most cited article focuses on natural emulsifiers in biopolymers, suggesting that research is centered on optimizing the stability and performance of these materials.

The assessment of scientific collaboration networks highlights the presence of clusters that facilitate knowledge exchange, with key researchers such as Guo, Peixuan and Haque, Farzin, who have contributed influential studies in the field. Moreover, the most frequently used keywords reflect the intersection between nanotechnology and food applications, reinforcing the significance of these materials in the packaging industry.

The predominance of review papers in publications underscores the need to consolidate fundamental concepts and evaluate technological advances rather than focusing solely on isolated experimental studies.

In conclusion, nanotechnology applied to biopolymers has proven to be an effective tool for enhancing sustainable packaging, helping to reduce environmental impact and advancing research in biodegradable materials. Strengthening collaborative networks and refining bibliometric methodologies will guide future research toward strategic areas that improve the performance of biopolymers in industrial and ecological applications, ensuring their feasibility in the global market.

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