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Mapping the Landscape of Nanotechnology Applications in Food Processing, Quality and Security: A Bibliometric Perspective

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Abstract

This study presents a bibliometric analysis of nanotechnology applications in food processing, quality, and security, highlighting the growing significance of nanoscale innovations in enhancing food safety, improving quality, extending shelf life, and promoting sustainability. Using data extracted from the Scopus database, this analysis employs Biblioshiny and VOSviewer software to map the intellectual structure and trends in this interdisciplinary field. The analysis reveals a steady increase in annual scientific production, with significant growth observed in the last five years, emphasizing the expanding relevance of this research. Key contributors include prolific authors such as David Julian McClements and leading sources like Nanotechnology in the Life Sciences. Global scientific production is dominated by countries like India, the United States, and China, with strong regional collaborations observed in Europe, Asia, and Latin America. Trending topics indicate a shift from foundational studies to advanced applications, focusing on themes like food safety, nanoparticles, and biosensors, as well as emerging areas such as artificial intelligence and sustainability. The thematic map categorizes topics into motor, basic, niche, and emerging themes, highlighting the dynamic evolution of the research landscape. The co-occurrence of keywords uncovers seven thematic clusters, emphasizing the integration of nanotechnology with agriculture, food packaging, and analytical methods. The study also examines international collaborations, illustrating the critical role of partnerships between developed and emerging economies in driving innovation. Overall, the findings underscore the global, interdisciplinary, and collaborative nature of this field, offering valuable insights for future research and policy development. This comprehensive analysis provides a roadmap for advancing nanotechnology applications to address pressing challenges in food processing, quality, and security.

Keywords: Nanotechnology, Food Processing, Food Quality, Food Security, Bibliometric Analysis, Biblioshiny, VOSviewer

1. Introduction

Nanotechnology, the manipulation of matter at the atomic and molecular scale, is revolutionizing numerous industries, including food processing, quality assurance, and security [1], [2]. By applying nanoscale innovations, scientists and engineers can address critical challenges such as food spoilage, contamination, and nutritional enhancement [3]. Nanotechnology offers cutting-edge solutions that enhance the safety, quality, and sustainability of food systems, ensuring that global demands are met while reducing

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environmental impact [4], [5]. This transformative technology is reshaping traditional food practices, bringing unprecedented precision and efficiency to the industry [6], [7].

One of the most impactful applications of nanotechnology is in food processing, where it is used to improve texture, flavor, and shelf life [8], [9]. Nanoparticles and nanostructures can be incorporated into food formulations to enhance sensory properties and create functional foods with additional health benefits [10]. For example, nanoemulsions are being employed to deliver bioactive compounds, such as vitamins and antioxidants, in a highly bioavailable form [11], [12]. These advancements not only improve consumer satisfaction but also address malnutrition and public health issues by fortifying foods with essential nutrients [8].

Nanotechnology also contributes significantly to maintaining food quality and safety through the development of advanced packaging solutions and detection systems [1], [13]. Nano-based packaging materials are designed to provide superior barrier properties against oxygen, moisture, and microbial contamination, thus extending the freshness and shelf life of food products [14]. Additionally, intelligent packaging systems embedded with nanosensors can monitor and indicate the freshness of food in real-time, enabling consumers and suppliers to make informed decisions [15]. These technologies reduce food waste and enhance trust in the safety of packaged goods [16].

In the context of food security, nanotechnology addresses global challenges related to agricultural production, resource optimization, and contamination prevention [17], [18]. Nano-fertilizers and nano-pesticides enhance crop yield and minimize environmental harm by ensuring precise delivery of active ingredients, reducing wastage, and lowering chemical runoff [17]. Furthermore, nanoscale filtration systems provide access to clean water for irrigation and consumption, an essential factor in ensuring sustainable food production [19]. The integration of nanotechnology into food systems promises a future where quality, safety, and security are maintained, contributing to the well-being of societies worldwide [20].

Nanotechnology has become a pivotal field in advancing food processing, quality assurance, and security by introducing innovative solutions to enhance food safety, extend shelf life, and improve nutritional value [14], [20]. With an increasing number of scientific studies exploring this interdisciplinary domain, bibliometric analysis offers a systematic approach to understanding the research landscape [21], [22]. Tools such as provide robust methodologies to analyze publication trends, research collaborations, and thematic evolution in this field [23], [24]. By leveraging these tools, this study aims to map the intellectual structure and emerging trends in nanotechnology applications for food systems.

Biblioshiny, a powerful application in the R programming environment, enables researchers to generate comprehensive bibliometric visualizations and metrics [25], [26]. It allows for the exploration of key parameters such as the most cited authors, institutions, journals, and keywords related to nanotechnology in food science [27]. Additionally, it provides thematic maps and temporal trend analyses that highlight shifts in research priorities over time, such as the growing focus on nano-packaging, nano-sensors, and nano-biosensors for food safety and quality enhancement.

Complementing Biblioshiny, VOSviewer specializes in creating network visualizations that depict co-authorship, co-citation, and keyword co-occurrence [28], [29]. These visualizations reveal clusters of related research areas and collaborations between countries and institutions, providing insights into global contributions and knowledge dissemination [30]. By integrating

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the findings from Biblioshiny and VOSviewer, this bibliometric analysis not only identifies influential works and emerging themes but also uncovers gaps in the current literature. These insights are invaluable for guiding future research and fostering interdisciplinary collaboration to address pressing challenges in food processing, quality, and security through nanotechnology.

2. Materials and Methods

We gathered the scientific publications related to the investigation from the Scopus database [31], [32], [33]. We retrieve bibliographic data using a search query such as (TITLE-ABS-KEY (nanotechnology) AND TITLE-ABS-KEY (food) AND TITLE-ABS-KEY (processing) OR TITLE-ABS-KEY (security) OR TITLE-ABS-KEY (quality)). The search was not restricted to any particular language, and the data included articles from peer-reviewed journals, books, book chapters, and conference papers. We collected 1156 articles from 726 different sources, spanning 2001 to 2021. To ensure accuracy, we screened the Scopus records to remove any duplicates. The results were saved as a "CSV" file, and we performed bibliometric analysis on the data using VOSviewer and Biblioshiny software.

3. Results and Findings

3.1.Main Information of the investigation

Table 1 provides a detailed overview of the bibliometric analysis of nanotechnology applications in food processing, quality, and security, spanning 2001 to 2021, revealing significant growth and global interest in the field. With a total of 1,156 documents published across 726 sources, the annual growth rate of 29.68% highlights the expanding relevance of this interdisciplinary research. Each document, on average, receives 32.28 citations, reflecting its academic and industrial impact. The dataset includes over 73,528 references, with 7,822 Keywords Plus and 3,183 Author's Keywords, indicating diverse research themes. Collaboration is a prominent feature, with 4,030 authors contributing, an average of 3.91 co-authors per document, and 19.2% of publications involving international co-authorships. The primary publication types are journal articles (548), book chapters (466), and conference papers (142), emphasizing the dominance of journal contributions. The average document age of 7.96 years suggests a balanced mix of foundational and recent studies. Overall, the analysis underscores the rapid development and collaborative nature of this impactful field.

Table 1. Main information of the investigation

Description	**Results**
MAIN INFORMATION ABOUT DATA	
Timespan	2001:2021
Sources (Journals, Books, etc)	726
Documents	1156
Annual Growth Rate %	29.68
Document Average Age	7.96
Average citations per doc	32.28
References	73528
DOCUMENT CONTENTS	
Keywords Plus (ID)	7822

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Author's Keywords (DE)	3183
AUTHORS	
Authors	4030
Authors of single-authored docs	158
AUTHORS COLLABORATION	
Single-authored docs	183
Co-Authors per Doc	3.91
International co-authorships %	19.2
DOCUMENT TYPES	
Article	548
book chapter	466
conference paper	142

3.2. Annual Scientific Productions

Figure 1 illustrates the annual scientific production, highlighting a steady upward trajectory from 2001 to 2021, reflecting growing global interest and advancements in this field. Starting with just one article in 2001, the output gradually increased, reaching seven articles by 2004 and experiencing a steady rise through 2013, with an annual production of 56 articles. A significant surge is observed from 2016 onward, with 81 articles that year, followed by consistent growth, culminating in a peak of 181 articles in 2021. This rapid increase, particularly over the last five years, highlights the expanding recognition of nanotechnology's potential to address critical challenges in food safety, quality, and security, demonstrating a robust research interest and interdisciplinary collaboration.

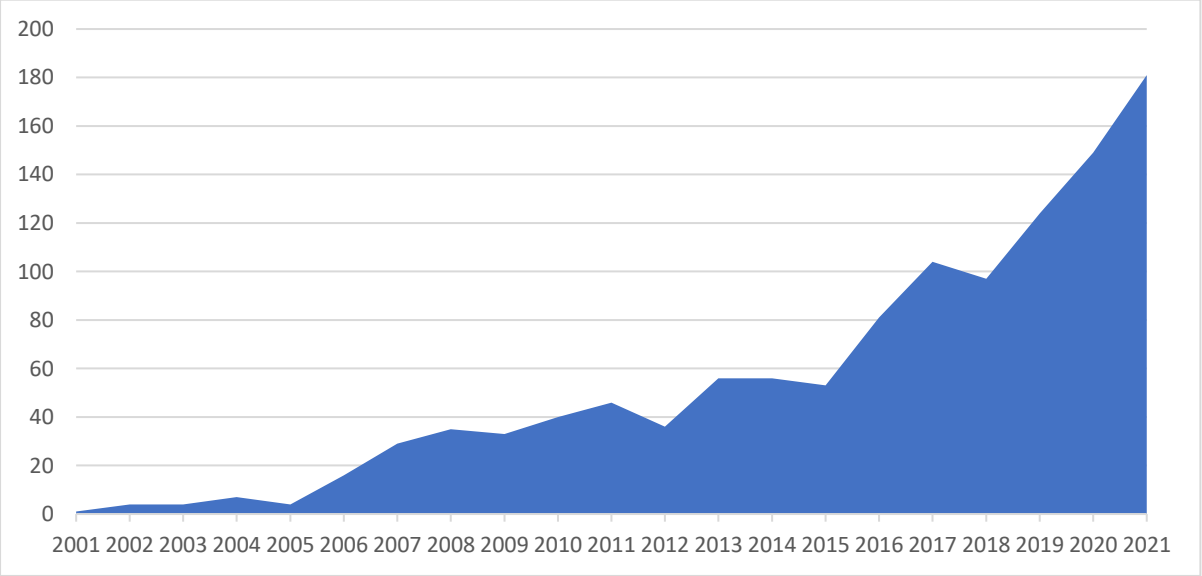

Figure 1. Annual scientific production

3.3. Most Relevant Authors

Figure 2 showcases the most prolific authors contributing to the field of nanotechnology applications in food processing, quality, and security, based on the number of publications. David Julian McClements leads with 9 articles, reflecting his significant influence and active participation in this domain. M.A. Cerqueira and A.A. Vicente follow closely with 8 articles each, highlighting their substantial contributions to advancing the field. Gustavo F. Gutiérrez-López has 7 publications, further underscoring his role in shaping research in this area.A group of six authors, including C. Anandharamakrishnan, Jose M. Lagaron, Jeyabalan Sangeetha, Devarajan Thangadurai, and Jason C.

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White, have each contributed 6 articles, demonstrating their active engagement in this interdisciplinary field. These authors represent a key segment of the research community driving innovation and knowledge dissemination in nanotechnology applications related to food systems. Their work collectively reflects the collaborative and growing nature of the research landscape.

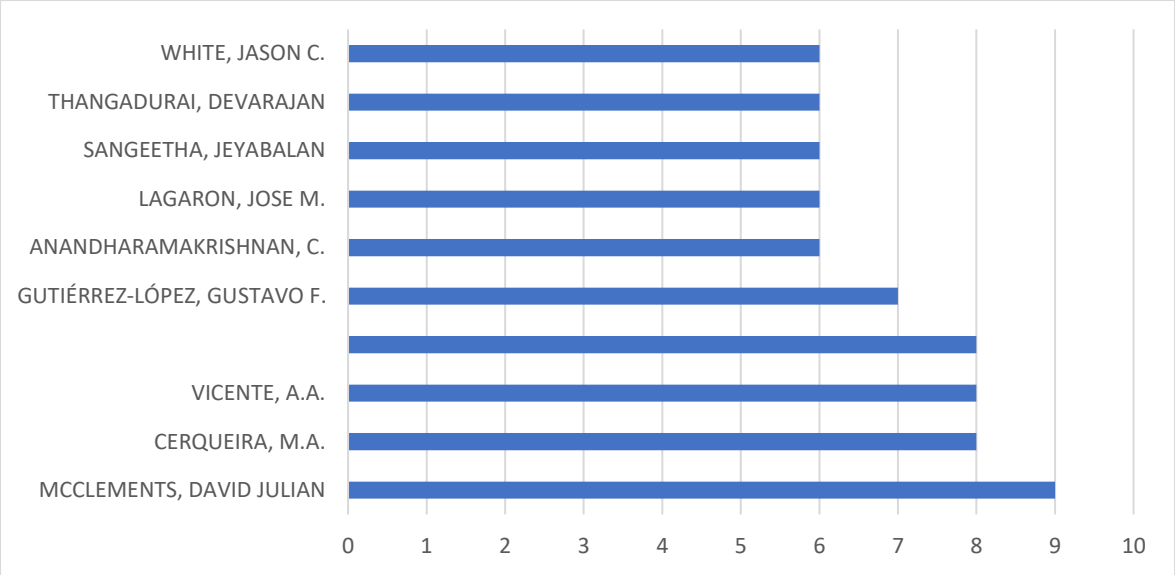

Figure 2. Most relevant authors

3.4. Most relevant sources

The table highlights the most relevant sources contributing to the field of literature's role in performing arts based on the number of articles published. Medical Problems of Performing Artists leads with 10 articles, emphasizing its significant focus on the intersection of health, performance, and artistic disciplines. New Theatre Quarterly follows with 6 articles, indicating its strong association with theatrical studies and literature. Arts and the Market and the Journal of Arts Management Law and Society each contribute 5 articles, reflecting their focus on the intersection of literature, performing arts, and cultural industries. Other notable sources, including Harmonia: Journal of Arts Research and Education and the Journal of Cultural Economics, with 4 articles each, explore diverse aspects such as education and the economic dimensions of cultural practices. Sources like Developments in Marketing Science and the International Journal of Arts Management, each with 3 articles, indicate the growing interdisciplinarity of the research, connecting performing arts to marketing, management, and policy studies. The inclusion of IOP Conference Series: Earth and Environmental Science suggests some cross-disciplinary studies, perhaps linking performing arts with environmental themes. Overall, the diversity of sources underscores the interdisciplinary nature of this research area, spanning health, education, economics, management, and policy domains. This distribution reflects the rich complexity and broad relevance of literature's role in performing arts.

Table 2. Most relevant sources

Sources	Articles
NANOTECHNOLOGY IN THE LIFE SCIENCES	24
FOOD TECHNOLOGY	12
FOOD ENGINEERING SERIES	11
FOOD RESEARCH INTERNATIONAL	10

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MULTIFUNCTIONAL AND NANOREINFORCED POLYMERS FOR FOOD PACKAGING	10
PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING	10
IMPACT OF NANOSCIENCE IN THE FOOD INDUSTRY	9
ACTA HORTICULTURAE	8
CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION	8
INTERNATIONAL JOURNAL OF BIOLOGICAL MACROMOLECULES	8

3.5. Country Scientific Production

Figure 3 illustrates the data on country scientific production, highlighting the global scientific production on nanotechnology applications in food processing, quality, and security, which is led by India, with 872 publications, indicating its strong research focus in this field. The United States follows with 624 publications, showcasing its leadership in advancing innovative applications and interdisciplinary collaboration. China, with 417 contributions, is another prominent player, reflecting its commitment to research and development in nanotechnology. European countries like Italy (223) and Spain (149) also demonstrate significant contributions, emphasizing their role in the global research network. Countries in Latin America, such as Brazil (151) and Mexico (149), contribute notably, reflecting the growing research interest in regions outside traditional industrial hubs. Additionally, countries like Iran (142) and Pakistan (112) highlight increasing contributions from the Middle East and South Asia, showcasing their emerging presence in this scientific domain. The United Kingdom, with 94 publications, represents significant research activity within Europe. Overall, the geographic distribution emphasizes the global nature of research on nanotechnology in food systems, with contributions from both developed and developing nations, reflecting a shared commitment to addressing food safety, quality, and sustainability challenges.

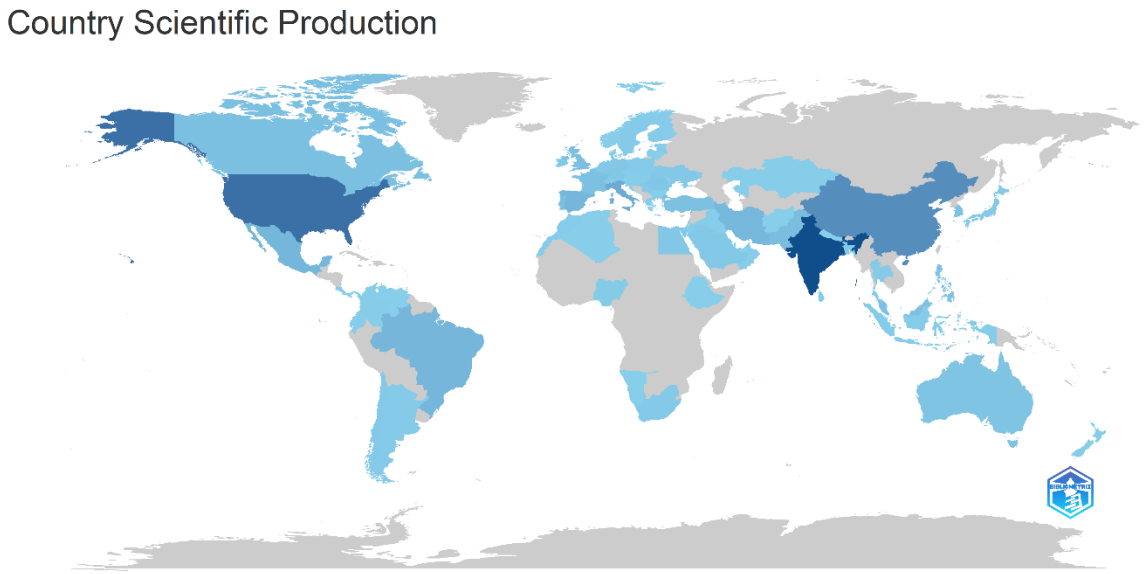

Figure 3. Country scientific production

3.6. Trend Topics

Figure 4 illustrates the evolving research trends in nanotechnology applications for food processing, quality, and security from 2001 to 2021, with term frequencies represented by bubble sizes. Early research (2001–2006) focused on foundational concepts like lactose and reverse osmosis, while later years (2006 onward) saw a shift toward applied topics such as food safety, food packaging, particle size, and antimicrobial activity. Dominant themes like nanoparticles, metal nanoparticles, and titanium

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dioxide highlight the growing interest in enhancing food preservation and quality. The inclusion of methodologies such as scanning electron microscopy and Fourier transform infrared spectroscopy reflects increasing sophistication in research techniques. Emerging topics like artificial intelligence in recent years signal the integration of nanotechnology with digital innovations, while terms such as environmental management and crop production demonstrate an expanding interdisciplinary focus on sustainability and public health. This progression underscores a consistent shift from foundational studies to advanced applications addressing global food security challenges.

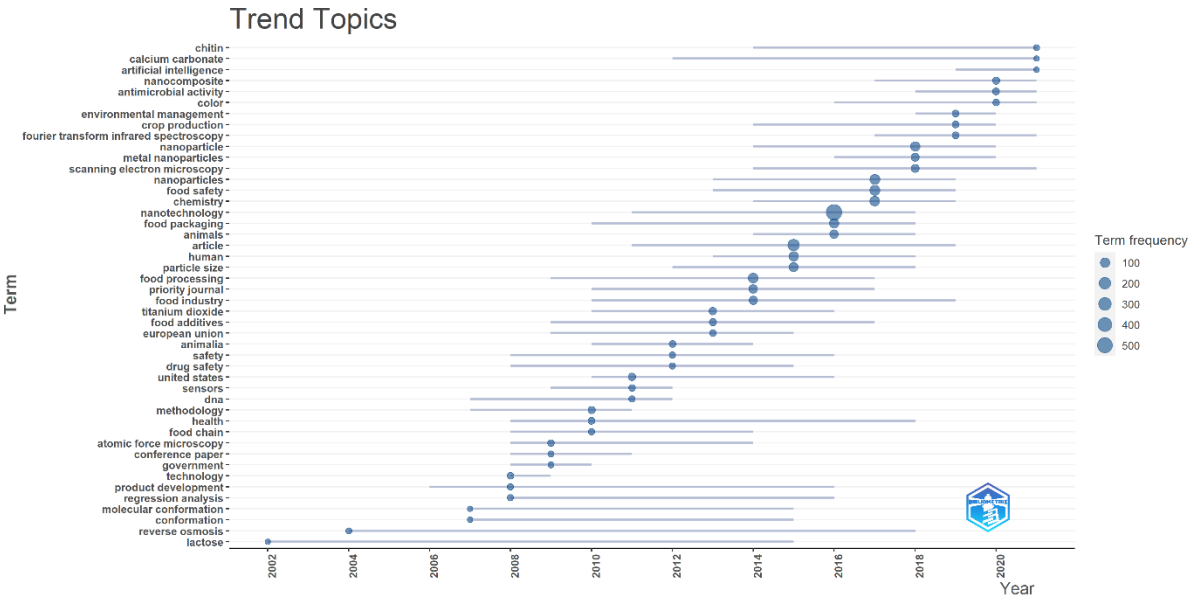

Figure 4. Trending topics in the realm of research

3.7. Thematic Map

Figure 5 visualizes the thematic map and categorizes research topics in nanotechnology applications for food processing, quality, and security into four quadrants based on their relevance (centrality) and development (density). Motor themes, located in the top-right quadrant, are highly relevant and well-developed, including critical topics like nanotechnology, nanoparticles, and food safety. These themes represent the backbone of the field, reflecting their central role in driving advancements and their strong interdisciplinary connections. These topics address global challenges in food preservation, safety, and quality and are pivotal in defining the research landscape. The basic themes in the bottom-right quadrant, such as nanomaterials, nanosensors, and agriculture, play a foundational role in the field. While these themes are highly relevant, their lower density suggests that they have room for further exploration and refinement, particularly in developing practical applications in agricultural technologies and sensor-based systems.

The top-left quadrant houses niche themes like abiotic stresses, quantum dots, and carbon nanotubes, which are well-developed but less connected to broader research, reflecting their importance in specialized applications. These areas, while advanced, have narrower use cases but significant potential in material science and stress management in food systems. The emerging or declining themes in the bottom-left quadrant, such as staphylococcus aureus and electrospinning, are either gaining traction as new areas of research or losing relevance over time. These themes may require further focus to either integrate them into broader research frameworks or re-evaluate their applicability in the field. Overall, the map illustrates a dynamic research landscape, with core themes driving innovation and niche or emerging areas offering opportunities for future exploration.

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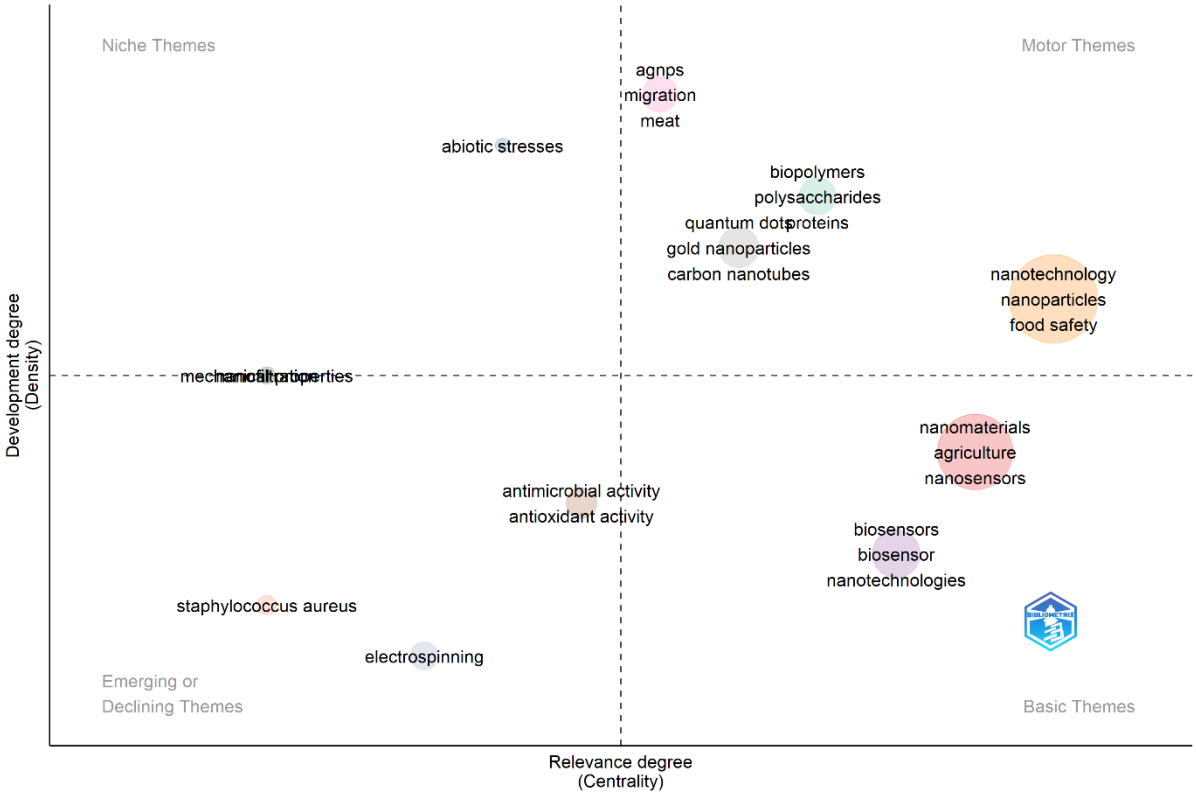

Figure 5. Thematic visualisation of author keywords

3.8. Co-occurrence of keywords

Figure 6 illustrates the co-occurrence network of keywords and reveals the intricate interconnections and thematic focus areas in research on nanotechnology applications for food processing, quality, and security. Out of 9,756 keywords, 688 met the minimum threshold of five occurrences, categorized into seven distinct clusters. The largest cluster (Cluster 1, 166 items) centers around nanotechnology, nanostructured materials, and biosensors, highlighting the field's core technological focus. This cluster emphasizes innovations aimed at enhancing food safety and quality, with significant mentions of food contamination, chemical sensors, and intelligent packaging, demonstrating the importance of nanotechnology in ensuring consumer safety and extending shelf life.

Other clusters further diversify the research themes. Cluster 2 (148 items) focuses on agriculture, food security, and nanofertilizers, underscoring the role of nanotechnology in sustainable agriculture and addressing global food challenges. Cluster 3 (135 items) highlights analytical techniques and material characterization with keywords like chemistry, scanning electron microscopy, and food analysis, reflecting the foundational research required for advancing nanotechnology. Meanwhile, Cluster 4 (90 items) explores innovations in sensing technologies, including biosensors and biosensing techniques, which are crucial for real-time food quality monitoring and contamination detection. Cluster 5 (78 items) bridges food and pharmaceutical applications, focusing on terms like drug safety, nanoemulsions, and biological availability.

Smaller clusters provide additional focus areas, such as Cluster 6 (68 items), which delves into packaging materials, intelligent packaging, and coatings, highlighting advancements in food preservation technologies. The smallest cluster, Cluster 7 (3 items), potentially represents niche or emerging areas, warranting further investigation. Overall, the network reflects a balanced mix of foundational, applied, and emerging themes, showcasing the interdisciplinary nature of the field. The dominance of keywords like nanotechnology and biosensors, along with strong connections across clusters, underscores the critical role of technological innovation in tackling pressing food safety and

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sustainability issues. This comprehensive mapping of keywords provides a roadmap for future research directions and highlights areas ripe for deeper exploration and innovation.

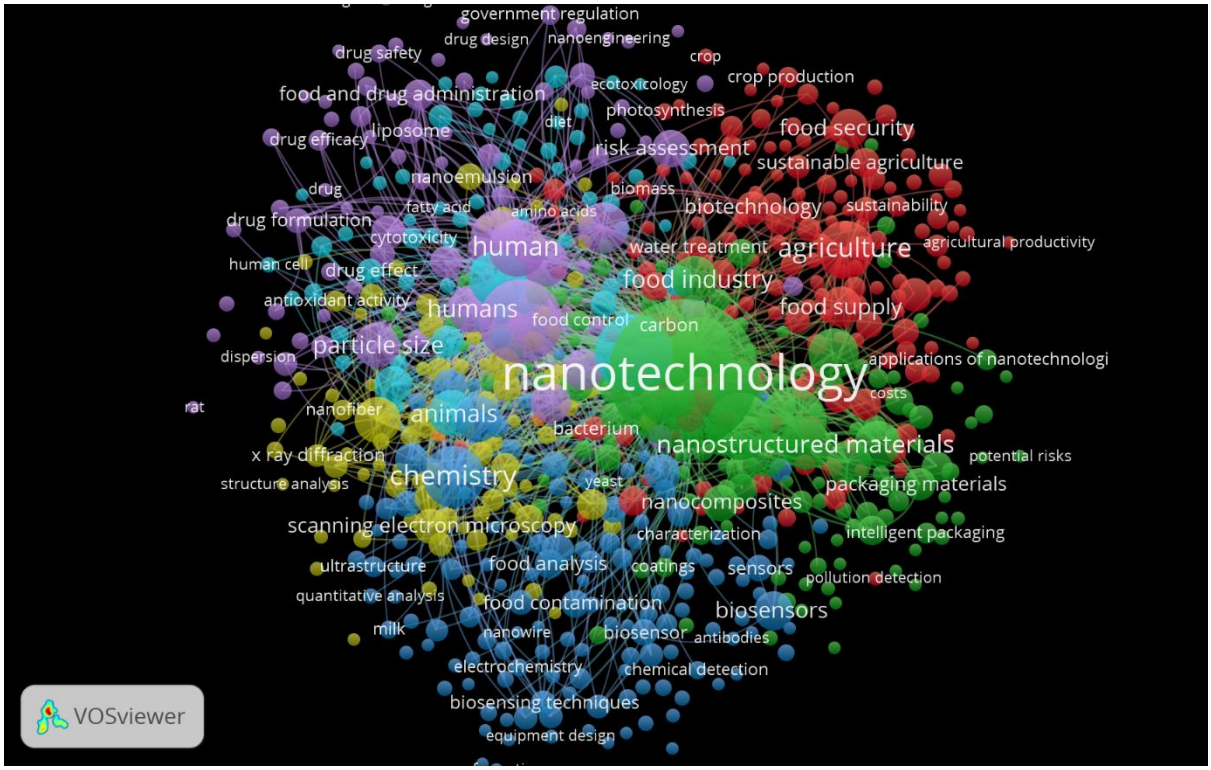

Figure 6. Co-occurrence of all keywords

3.9. Countries Collaborations

Figure 7 depicts the co-authorship network of countries in nanotechnology applications for food processing, quality, and security, comprising 51 countries organized into eight distinct clusters based on collaboration patterns. Major contributors like India, United States, and China dominate the network, represented by the largest nodes, indicating their high publication output and active participation in international collaborations. The United States stands out as a global hub with widespread connections to countries across all regions, while India and China also exhibit strong regional and international ties, particularly with countries in Asia, Europe, and North America. Countries like Pakistan, Malaysia, and Turkey are closely linked to India, showcasing active regional partnerships within South Asia and its neighboring regions.

Regional clusters highlight distinct collaboration patterns. For instance, one cluster focuses on European countries like Germany, Italy, Netherlands, and Finland, which show robust intra-European collaborations along with links to global hubs such as the United States and China. Another cluster connects China, Saudi Arabia, and South Africa, reflecting China's engagement with countries in the Middle East and Africa. Similarly, the United States forms a major cluster with collaborators from Canada, South Korea, and other East Asian nations, indicating the prominence of transcontinental partnerships. Smaller but significant contributors, such as Serbia, Chile, and Israel, participate in regionally concentrated partnerships while maintaining connections to leading nations.

The network illustrates the global nature of research in nanotechnology applications, emphasizing the interplay between developed and developing nations. Emerging economies like India, China, and Pakistan demonstrate significant research activity and integration into international collaborations, contributing to knowledge dissemination and innovation in the field. While prominent hubs dominate

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the network, the presence of distinct clusters underscores the importance of regional collaborations in driving advancements. The network also highlights opportunities to enhance participation from less-connected nations, fostering equitable growth and global knowledge sharing to address food safety and security challenges through nanotechnology.

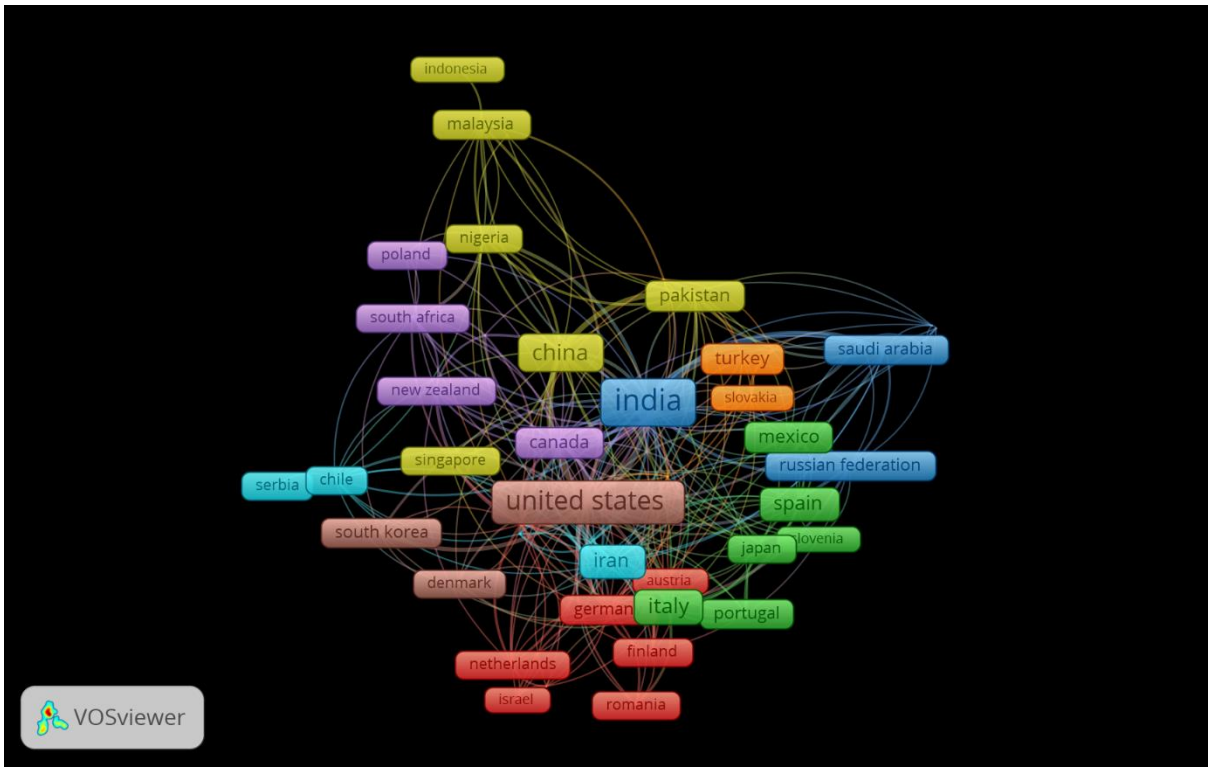

Figure 7. Countries collaborations

4. Discussions

The bibliometric analysis of nanotechnology applications in food processing, quality, and security highlights significant growth in research activity over the last two decades. The annual scientific production shows a consistent upward trajectory, culminating in a sharp increase in the last five years, emphasizing the expanding recognition of nanotechnology's role in addressing food safety and sustainability challenges. With a total of 1,156 documents from 726 sources and an annual growth rate of 29.68%, the field is experiencing robust interdisciplinary collaboration and innovation. The involvement of over 4,030 authors, averaging 3.91 co-authors per document, and 19.2% of publications involving international co-authorships demonstrates the global and cooperative nature of this research area.

The thematic and keyword analyses reveal a balanced mix of foundational, applied, and emerging topics. Dominant themes such as nanotechnology, nanoparticles, and food safety drive the field, while keywords like biosensors and intelligent packaging indicate strong research interest in monitoring and preservation technologies. Basic themes, including nanomaterials and nanosensors, play a crucial foundational role, with potential for further refinement and practical applications in agriculture and food systems. Meanwhile, emerging topics like artificial intelligence and environmental management highlight the integration of digital and sustainable practices. The co-occurrence network underscores the critical role of technological innovation and interdisciplinary collaboration in advancing food quality and security.

Global collaboration networks further support these findings, with significant contributions from both developed and emerging economies. Countries like India, the United States, and China lead the field,

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demonstrating their strong research capacity and international partnerships. Regional clusters in Europe, Asia, and Latin America underscore the importance of localized collaboration in addressing specific food system challenges, while transcontinental links emphasize the interconnected nature of this research. These findings highlight the importance of continued investment in collaborative and innovative research to enhance food safety, quality, and sustainability through nanotechnology.

5. Conclusion

The bibliometric analysis of nanotechnology applications in food processing, quality, and security highlights the rapid growth and global importance of this field, driven by key themes such as food safety, nanoparticles, and biosensors, along with emerging areas like artificial intelligence and sustainability. With significant contributions from leading countries like India, the United States, and China, the research underscores the collaborative and interdisciplinary nature of advancements in nanotechnology for food systems. The thematic and keyword analyses reveal a balanced research landscape, integrating foundational, applied, and emerging topics. To further enhance this field, it is recommended to strengthen international collaborations, particularly with underrepresented regions, to foster equitable growth; prioritize investment in areas like intelligent packaging, nanosensors, and AI integration to address evolving food safety challenges; and bridge nanotechnology with sustainability and public health initiatives for broader societal impact. These actions will ensure the continued evolution of nanotechnology as a transformative tool for addressing global food safety, quality, and sustainability challenges.

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