

Mapping the Growth of Nanotoxicology: A Bibliometric Perspective on Emerging Trends and Key Publications

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Nanotoxicology is an emerging field that examines the toxicological impacts of nanomaterials on biological systems, focusing on mitigating potential risks to human health and the environment. This study presents a comprehensive bibliometric analysis of nanotoxicology research using data retrieved from the Scopus database. The analysis, conducted with Biblioshiny and VOSviewer software, explores key aspects such as annual scientific production, prominent authors, influential sources, and global research contributions. Results indicate significant growth in the field, with an annual production increase of 32.86%, reflecting heightened interest and collaborative efforts. China and the United States lead global research output, highlighting strong international partnerships but also emphasizing the need for greater contributions from underrepresented regions. Emerging trend topics, including "nanoplastics," "machine learning," and "metabolomics," signal a shift towards advanced technologies and interdisciplinary approaches. Thematic mapping reveals a well-established core of fundamental topics alongside niche and emerging areas requiring integration into broader research frameworks. Bibliographic coupling identifies influential documents and research clusters, underscoring the multidisciplinary nature of the field. Keyword co-occurrence and collaboration networks highlight the interconnectedness of research themes and the critical role of international

partnerships. These findings provide valuable insights for researchers, policymakers, and industry stakeholders, promoting the safe and sustainable development of nanomaterials.

Keywords: Nanotoxicology, Bibliometric Analysis, Biblioshiny, VOSviewer.

1. Introduction

Nanotoxicology is an emerging field of study that examines the potential toxic effects of nanomaterials on biological systems, including humans, animals, and the environment [1], [2]. Nanomaterials, characterized by their nanoscale dimensions ranging from 1 to 100 nanometers, possess unique physical, chemical, and biological properties that differentiate them from their bulk counterparts [3], [4]. These materials are widely utilized across industries such as medicine, electronics, cosmetics, and energy, offering significant advancements in technology and innovation [5], [6]. However, the very properties that make nanomaterials valuable can also pose risks, necessitating a comprehensive understanding of their interactions with living organisms and ecosystems [2], [7].

One of the primary concerns in nanotoxicology is the ability of nanoparticles to penetrate biological barriers and accumulate in various tissues, potentially causing adverse effects [8]. Due to their small size, nanoparticles can evade the body's natural defense mechanisms and reach sensitive areas such as the brain, liver, or lungs [9]. Studies have shown that some nanoparticles can induce oxidative stress, inflammation, and DNA damage, leading to potential long-term health effects, including respiratory and cardiovascular diseases [10]. Furthermore, the lack of a standardized approach to evaluate nanoparticle toxicity complicates risk assessment and regulation [11].

Environmental implications of nanomaterials also play a critical role in nanotoxicology research [12], [13]. As nanomaterials are increasingly incorporated into consumer products, their eventual release into soil, water, and air raises concerns about their impact on ecosystems [13], [14]. For instance, nanoparticles may interact with microorganisms, plants, and aquatic life, potentially disrupting food chains and biodiversity [15]. The persistence and bioaccumulation of nanomaterials in the environment further amplify these concerns, highlighting the need for sustainable design and disposal practices to mitigate risks [16].

In response to these challenges, nanotoxicology integrates multidisciplinary approaches, combining principles of toxicology, material science, and biology to evaluate the safety of nanomaterials [17]. Advanced techniques, such as in vitro testing, computational modeling, and high-throughput screening, are employed to predict and assess nanoparticle toxicity [18]. This field also emphasizes the development of safer nanomaterials through green synthesis methods and regulatory frameworks. By addressing the potential risks associated with nanomaterials, nanotoxicology aims to ensure their safe and responsible application, promoting innovation while safeguarding human health and the environment [19].

Nanotoxicology, as a field of study, has seen rapid growth in recent decades due to the increasing applications and potential risks associated with nanomaterials [20], [21]. Understanding the trends, key contributors, and emerging areas of research in nanotoxicology is essential for guiding future studies and policy decisions. Bibliometric analysis offers a

powerful method to achieve this by quantitatively analyzing the scientific literature in the field [22], [23], [24]. Tools such as Biblioshiny, a user-friendly interface of the R-based Bibliometrix package, and VOSviewer, a software for creating and visualizing bibliometric networks, enable researchers to extract insights into publication trends, influential authors, and collaborative networks in nanotoxicology research .

Using Biblioshiny, researchers can perform comprehensive analyses of nanotoxicology publications, including citation analysis, keyword co-occurrence networks, and trend visualization [25], [26], [27]. This tool allows users to generate detailed descriptive statistics, evaluate the growth of publications over time, and identify high-impact journals and countries contributing to the field [28], [29]. By leveraging the interactive features of Biblioshiny, researchers can gain a nuanced understanding of the evolving landscape of nanotoxicology research and its multidisciplinary nature.

VOSviewer complements Biblioshiny by offering advanced visualization capabilities for mapping relationships among authors, institutions, and keywords in nanotoxicology. Its ability to create co-authorship and keyword networks enables the identification of research clusters and thematic areas [30], [31]. These visualizations provide an intuitive understanding of collaboration patterns and knowledge diffusion, helping to highlight emerging topics and gaps in the field [32]. Together, Biblioshiny and VOSviewer facilitate a robust bibliometric exploration of nanotoxicology, shedding light on its current status and future directions.

2. Materials and Methods

We collected the scientific publications related to the investigation from the Scopus database. [33], [34], [35]. We conducted a search using specific keyword “nanotoxicology”. 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 4001 articles from 948 different sources, spanning 2004 to 2023. 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 Bibloshiny software.

3. Results and Findings

3.1. Main Information of the investigation

Table 1 provides an extensive overview of the bibliometric analysis of nanotoxicology research from 2004 to 2023 and highlights key trends and collaboration patterns in the field. A total of 4,001 documents were published across 948 sources, with an impressive annual growth rate of 32.86%, indicating a significant expansion of interest and contributions to the field during this period. These publications have an average age of 7.43 years and boast an average citation count of 48.24 per document, underscoring their high impact and relevance in the scientific community. The data also includes 194,394 references, demonstrating the extensive foundation upon which the field has been built. In terms of research content, the presence of 23,083 "Keywords Plus" and 7,859 "Author Keywords" reveals the diversity of topics and areas of focus within nanotoxicology. The field has seen contributions from 17,241

authors, with only 131 authors publishing single-authored documents, emphasizing the collaborative nature of this research area. On average, there are 6.25 co-authors per document, and 27.19% of the works involve international co-authorship, reflecting the global interest and interdisciplinary collaboration driving advancements in nanotoxicology. The distribution of document types further demonstrates the prominence of journal articles, which account for 3,533 publications, followed by 336 book chapters and 132 conference papers. These findings illustrate the importance of peer-reviewed journals as the primary medium for disseminating research, while conference papers and book chapters provide complementary platforms for exploring emerging ideas and fostering scholarly dialogue. Together, this analysis highlights the dynamic growth and collaborative efforts characterizing nanotoxicology research..

Table 1. Main information of the investigation

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2004:2023
Sources (Journals, Books, etc)	948
Documents	4001
Annual Growth Rate %	32.86
Document Average Age	7.43
Average citations per doc	48.24
References	194394
DOCUMENT CONTENTS	
Keywords Plus (ID)	23083
Author's Keywords (DE)	7859
AUTHORS	
Authors	17241
Authors of single-authored docs	131
AUTHORS COLLABORATION	
Single-authored docs	146
Co-Authors per Doc	6.25
International co-authorships %	27.19
DOCUMENT TYPES	
article	3533
book chapter	336
conference paper	132

3.2. Annual Scientific Productions

Figure 1 illustrates the annual scientific production in nanotoxicology and demonstrates steady and significant growth in research output over the years. Starting with only one article in 2004, the field saw exponential growth, particularly between 2006 and 2017. By 2017, the number

of publications reached a peak of 388 articles, indicating heightened interest and activity in this domain. While there was a slight decline in subsequent years, the production remained robust, with an average of over 300 articles annually between 2015 and 2020. The drop in publications after 2020 could be attributed to external factors such as the COVID-19 pandemic, which may have disrupted research activities globally. However, even with a decline, the annual outputs for 2021 (260 articles), 2022 (222 articles), and 2023 (221 articles) reflect the sustained relevance of nanotoxicology as a research area. Overall, this trend underscores the maturation of nanotoxicology as a field, with a significant accumulation of knowledge and an expanding community of researchers contributing to its development.

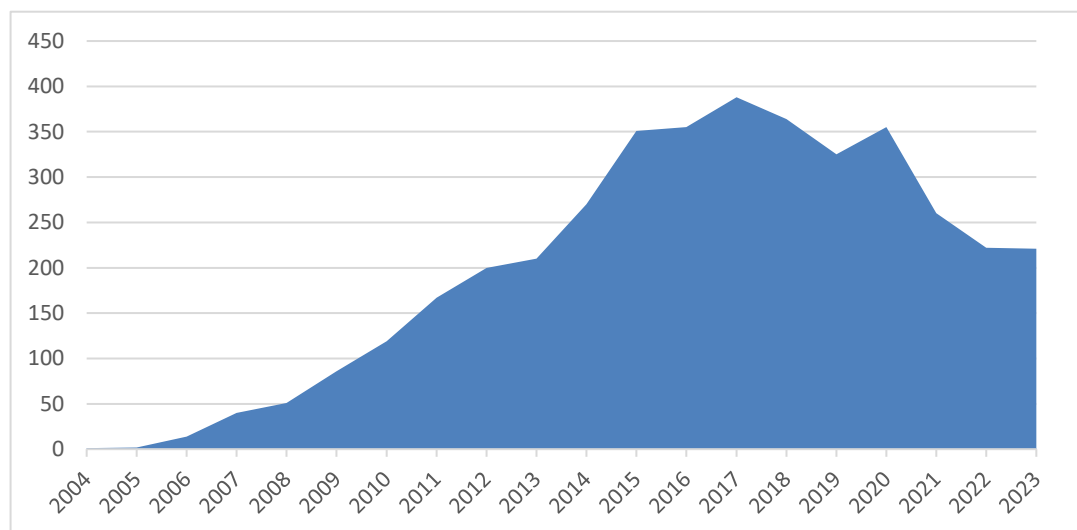


Figure 1. Annual scientific production

3.3. Most Relevant Authors

Figure 2 showcases the most relevant authors contributing to the field of nanotoxicology based on the number of publications. Philip Demokritou leads the list with 44 publications, indicating his significant influence and prolific contribution to the domain. He is followed by Vicki Stone with 32 publications and Vincent Castranova with 30 publications, both of whom are also key contributors. Other notable authors include Chunying Chen (26 publications), Iseult Lynch (24 publications), and Ulla Vogel (23 publications), all of whom have made substantial contributions to advancing the field. The distribution of publications among these authors reflects the collaborative and multidisciplinary nature of nanotoxicology research. These leading researchers have likely played pivotal roles in shaping the research agenda, exploring key topics such as the toxicological effects of nanoparticles, regulatory frameworks, and mitigation strategies. The consistent contributions by these authors underscore their expertise and commitment to addressing the challenges associated with nanomaterial applications.

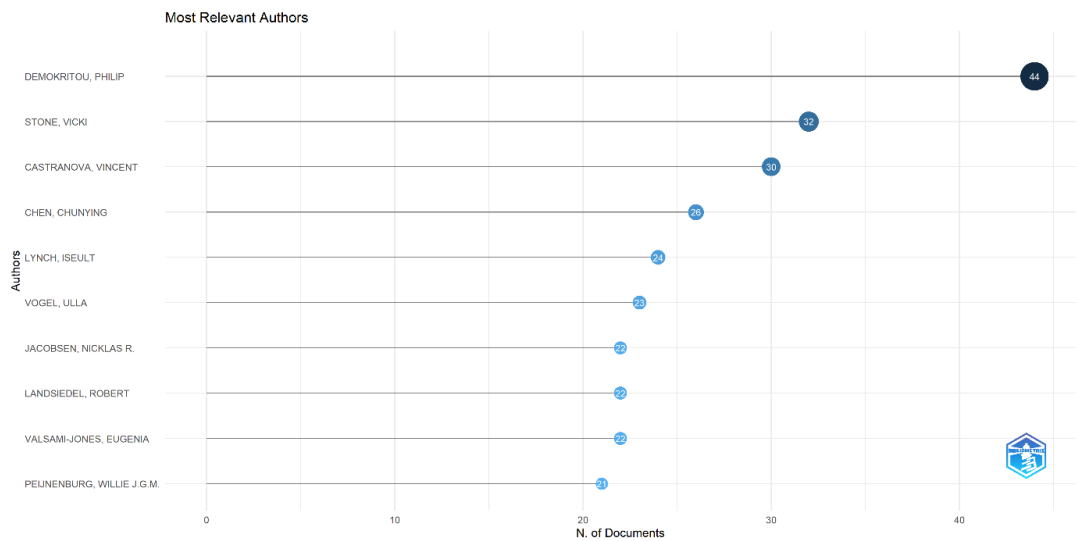


Figure 2. Most relevant authors

3.4. Most relevant sources

Table 2 highlights the most relevant sources contributing to nanotoxicology research, with Nanotoxicology leading the field at 328 articles, serving as the primary journal dedicated to exploring the toxicological effects of nanomaterials. Other significant contributors include Chemosphere (110 articles) and Science of the Total Environment (83 articles), which focus on the environmental implications of nanoparticles. Journals like Particle and Fibre Toxicology (80 articles) and the Journal of Hazardous Materials (78 articles) delve into the specific properties of nanoparticles that influence toxicity. The Journal of Nanoparticle Research (71 articles) and ACS Nano (56 articles) provide insights into broader applications and safety considerations. Meanwhile, Environmental Toxicology and Chemistry (64 articles) and Environmental Pollution (63 articles) address ecological and regulatory aspects, reflecting the field’s societal relevance. Finally, the International Journal of Nanomedicine (63 articles) bridges nanotoxicology with medical applications, emphasizing the safety and therapeutic potential of nanomaterials. Together, these sources underscore the interdisciplinary and dynamic nature of nanotoxicology research.

Table 2. Most relevant sources

Sources	Articles
NANOTOXICOLOGY	328
CHEMOSPHERE	110
SCIENCE OF THE TOTAL ENVIRONMENT	83
PARTICLE AND FIBRE TOXICOLOGY	80
JOURNAL OF HAZARDOUS MATERIALS	78
JOURNAL OF NANOPARTICLE RESEARCH	71
ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY	64

ENVIRONMENTAL POLLUTION	63
INTERNATIONAL JOURNAL OF NANOMEDICINE	63
ACS NANO	56

3.5. Country Scientific Production

Figure 3 highlights the global scientific production in nanotoxicology, with China leading as the most prolific contributor, producing 4,446 publications. The United States follows closely with 4,150 publications, reflecting its strong research infrastructure and investment in advanced nanotechnology. Germany (1,412), Italy (1,321), and Brazil (1,290) represent significant contributions from Europe and South America, showcasing the global reach and interest in nanotoxicology. India (1,247) and South Korea (692) indicate substantial research output from Asia, demonstrating regional expertise and focus on this emerging field. Other notable contributors include the UK (1,023), France (830), and Spain (544), underscoring the prominence of European nations in advancing nanotoxicology. The accompanying map visually emphasizes the geographic distribution of research activity, with darker shades indicating higher productivity. The concentration of research in countries like China and the USA highlights their leadership roles, while the contributions from Europe, Asia, and South America reflect a growing global interest in understanding and addressing the toxicological impacts of nanomaterials. This distribution also suggests the increasing interdisciplinary and collaborative efforts required to tackle the complex challenges associated with nanotechnology.

Country Scientific Production

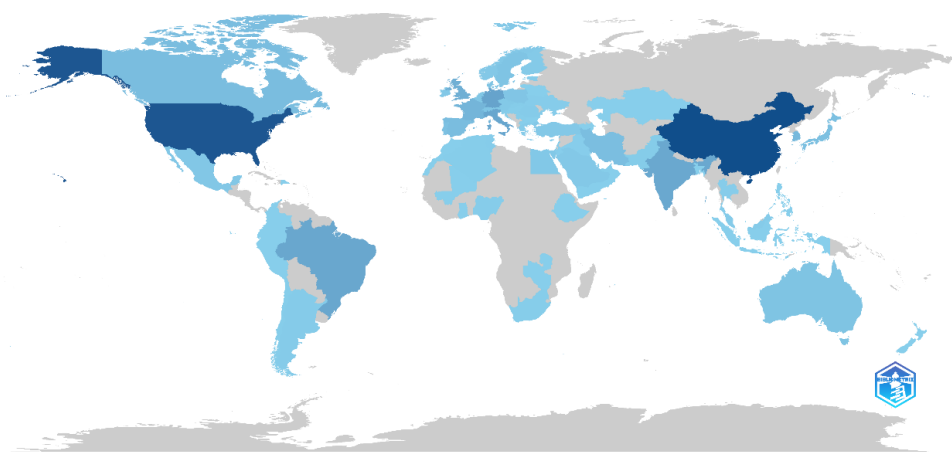


Figure 3. Country scientific production

3.6. Trend Topics

Figure 4 illustrates the evolving trend topics in nanotoxicology over time, highlighting key areas of research focus and emerging interests. Early studies in the field (2008-2012) were centered on fundamental terms like "nanotoxicology," "cytotoxicity," and specific nanomaterials such as "titanium dioxide," "gold nanoparticles," and "silica." As the field

advanced, newer terms such as "engineered nanomaterials," "silver nanoparticles," and "oxidative stress" gained prominence, reflecting a shift toward exploring the biological interactions and potential hazards of diverse nanoparticles. From 2016 onward, the research focus expanded to encompass cutting-edge topics such as "green synthesis," "machine learning," "transcriptomics," and "metabolomics," indicating a multidisciplinary approach to understanding nanoparticle effects and developing safer alternatives. Emerging areas like "nanoplastics," "cardiotoxicity," and "mixture toxicity" highlight concerns about environmental and human health impacts, as well as the complexity of nanoparticle exposure in real-world scenarios. The increasing size of the term frequency bubbles over time emphasizes the growing interest and importance of these topics, reflecting the field's dynamic and rapidly evolving nature. This visualization demonstrates the field's progression from foundational toxicology to integrating advanced methodologies and addressing broader societal challenges.

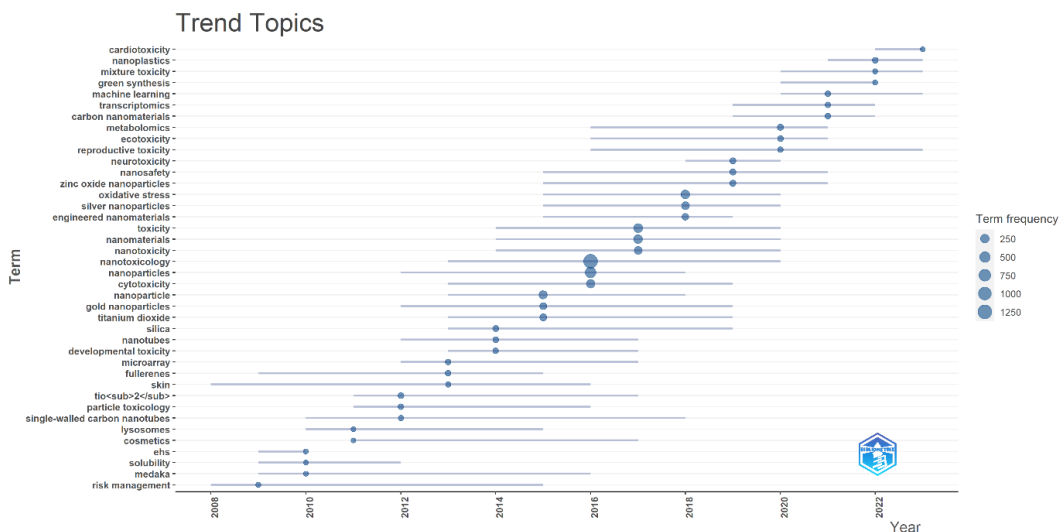


Figure 4. Trending topics in the realm of research

3.7. Thematic Map

Figure 5 provides a thematic map of nanotoxicology research, categorizing topics into four quadrants based on their centrality (relevance to the field) and density (level of development). In the Basic Themes quadrant (lower-right), fundamental topics such as "nanotoxicology," "article," and "controlled study" dominate. These themes are highly central to the field and widely studied, serving as the foundation of nanotoxicology research. Their widespread relevance and strong connections with other topics underline their critical role in shaping the understanding and progression of the field.

The Niche Themes quadrant (upper-left) includes specialized topics such as "toxicity," "silver nanoparticle," and "silver." These themes are well-developed and exhibit high density, indicating robust research focus within specific domains. However, their lower centrality suggests they are not broadly connected to the wider nanotoxicology research landscape. These topics often represent targeted studies addressing specific applications or toxicological

concerns, such as the impact of silver nanoparticles on biological systems. While vital for advancing niche knowledge, they have yet to achieve broader integration into the general framework of nanotoxicology.

The Emerging or Declining Themes quadrant (lower-left) includes topics such as "drug delivery system," "biocompatibility," and "cell line, tumor." These themes represent areas either gaining momentum or losing relevance in the field. Emerging topics like drug delivery systems could have potential for future growth as they intersect with nanomedicine and therapeutic applications. Meanwhile, the absence of themes in the Motor Themes quadrant (upper-right) indicates that no topics currently combine both high development and high relevance across the field. This suggests an opportunity for researchers to focus on developing key areas into motor themes, bridging the gap between specialized research and broad applicability in nanotoxicology.

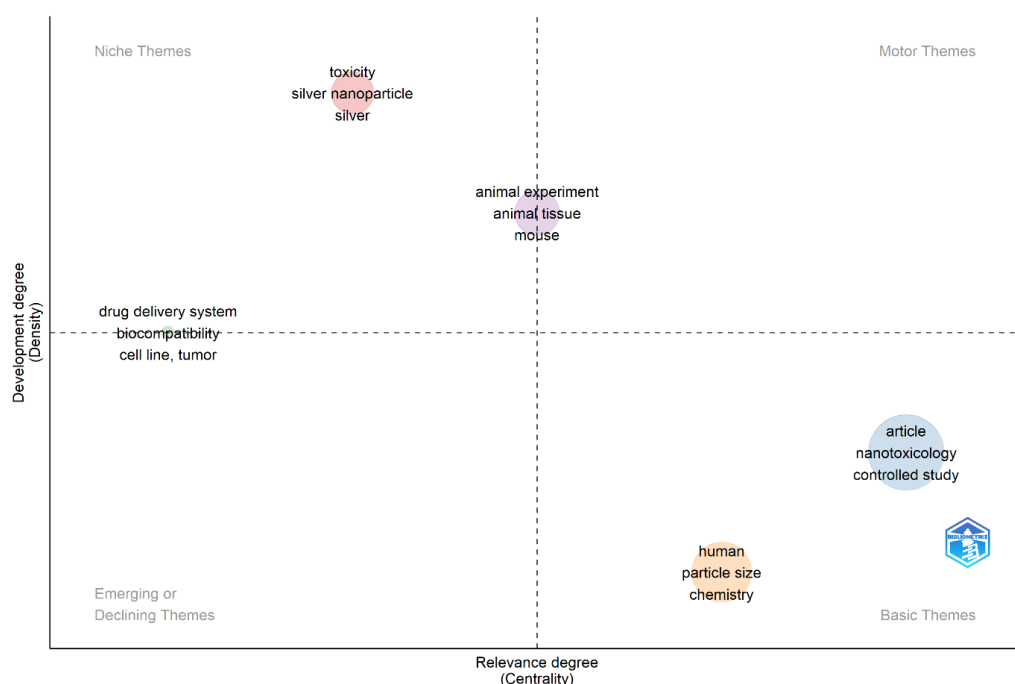


Figure 5. Thematic visualisation of author keywords

3.8. Bibliographic Coupling of Documents

Figure 6 represents the bibliographic coupling of documents in nanotoxicology, demonstrating the interconnectedness of scholarly works based on shared citations. By applying a minimum citation threshold of 20, a total of 2,521 items are included in the network, clustered into 11 distinct groups. This visualization highlights the development of research clusters and the areas of shared scholarly interest, showcasing the depth and breadth of the field. Key clusters, represented by larger and more prominent nodes such as "Huh (2010)," "Tenzer (2013)," and "Xia (2008a)," indicate highly cited and influential works within the field. These documents serve as central nodes, forming the backbone of their respective clusters and reflecting their importance in shaping the discourse in nanotoxicology. Each cluster represents a thematic

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focus, such as the toxicity of nanoparticles, risk assessments, or the environmental and health impacts of specific materials like silver nanoparticles or carbon nanomaterials. The interconnectedness of clusters signifies the multidisciplinary nature of nanotoxicology, integrating toxicology, material science, environmental studies, and health sciences. The clustering also reflects the emergence of collaborative research themes and the importance of foundational works in creating a cohesive scientific understanding. This bibliographic coupling map underscores the dynamic and collaborative efforts driving advancements in nanotoxicology while identifying influential documents and thematic research networks.

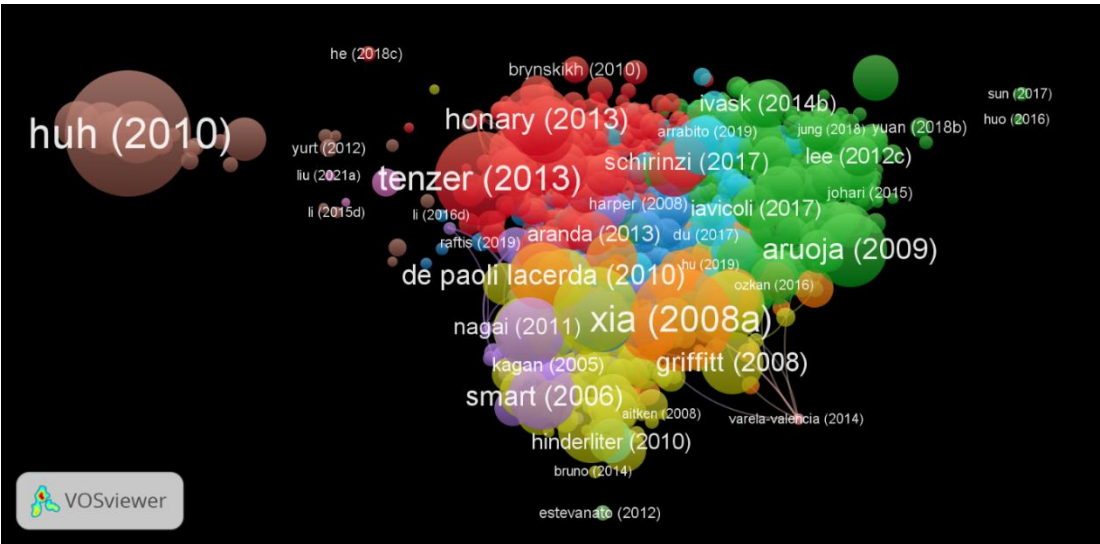


Figure 6. bibliographic coupling of documents

3.9. Co-occurrence of keywords

Figure 7 illustrates the co-occurrence network of author keywords in nanotoxicology research, providing insights into the interrelation and thematic structure of the field. With a minimum occurrence threshold of 10, the network comprises 186 keywords distributed across 8 clusters, each represented by a distinct color. The clusters vary in size, indicating the relative thematic focus within the field. Cluster 1 (41 keywords), represented in red, centers around foundational themes such as "nanotoxicology," "genotoxicity," and "cytotoxicity," which are crucial for understanding the biological impacts of nanomaterials. Cluster 2 (38 keywords), shown in green, focuses on applications like "nanomedicine," "drug delivery," and "biocompatibility," reflecting the intersection of nanotechnology with therapeutic and biomedical applications. Similarly, Cluster 3 (33 keywords), in blue, explores cellular-level impacts, emphasizing terms like "apoptosis," "cell viability," and "ROS" (reactive oxygen species), highlighting studies on oxidative stress and cellular health.

Other clusters provide niche or emerging insights. For instance, Cluster 4 (26 keywords), in yellow, includes terms such as "risk assessment," "carbon nanomaterials," and "aquatic toxicology," underlining environmental and regulatory concerns. Cluster 5 (20 keywords), in purple, features "particle toxicology" and "exposure," emphasizing health and safety considerations. Smaller clusters like Cluster 6 (15 keywords) and Cluster 7 (9 keywords) deal

with advanced topics such as "metabolomics," "proteomics," and "biomarkers," reflecting a growing interest in molecular and diagnostic approaches. Finally, Cluster 8 (4 keywords), the smallest cluster, represents niche areas, potentially pointing to highly specialized or emerging themes. Overall, the network demonstrates the multidimensional and interdisciplinary nature of nanotoxicology research. The clustering and interconnections between keywords reflect both the foundational and cutting-edge areas of study, providing a roadmap for identifying research gaps and potential areas of collaboration.

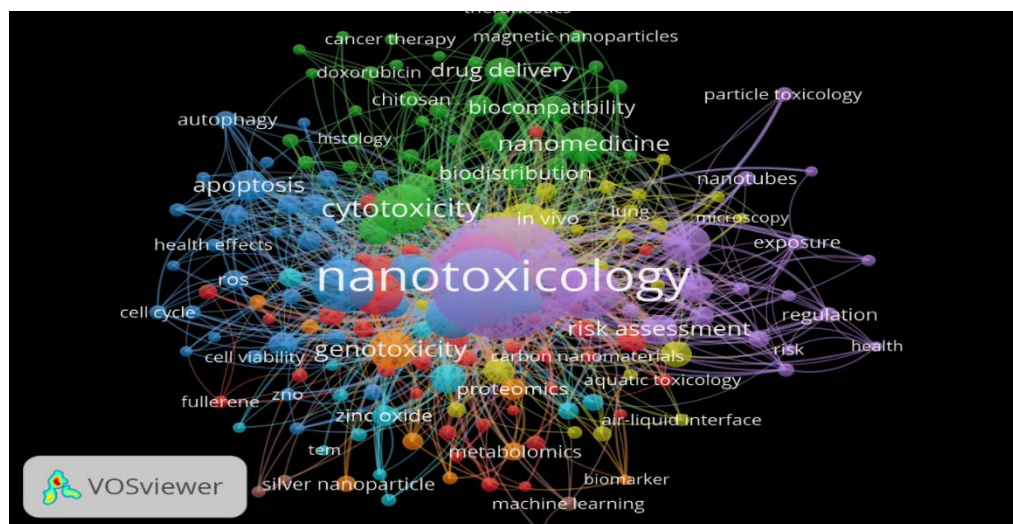


Figure 7. Co-occurrence of all keywords

3.10. Countries Collaborations

Figure 8 depicts a network visualization of international collaborations among 61 countries in nanotoxicology research, organized into 6 distinct clusters. The United States emerges as the largest and most central node, signifying its pivotal role in fostering global research partnerships. It collaborates extensively with countries like China, India, Italy, and Switzerland, highlighting its influence across multiple clusters. China, another major node, demonstrates strong connections with nations such as Australia, Netherlands, and Singapore, indicating its growing prominence in international research efforts. European countries like Italy, Spain, Switzerland, and Denmark form a significant collaborative cluster, reflecting the region's robust intra-regional research ties. Other notable collaborations include Brazil and Argentina, representing South America's contributions, and smaller yet interconnected nodes like Malaysia, Portugal, and South Korea, which indicate active, emerging partnerships. The clustering and interconnectedness underscore the interdisciplinary and global nature of nanotoxicology research, driven by collaborative efforts to address shared challenges in nanomaterial applications and toxicology.

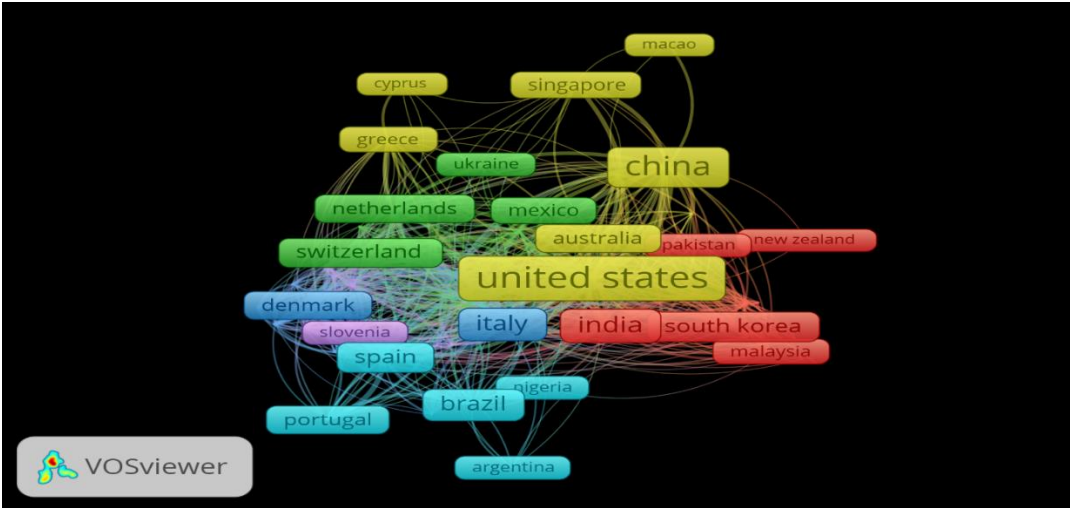


Figure 7. Countries collaborations

4. Discussions

The bibliometric analysis highlights significant growth and diversification in nanotoxicology research, with an annual growth rate of 32.86% over the past two decades. This rapid expansion underscores the increasing recognition of nanomaterials' potential toxicological impacts on human health and the environment. Despite a slight decline in output after 2020, likely due to the COVID-19 pandemic, the field remains robust, with over 200 publications annually. However, the uneven distribution of research output among countries, with China and the United States leading, points to the need for greater participation from underrepresented regions to ensure global inclusivity and a broader range of perspectives.

The co-occurrence of author keywords reveals an evolving thematic landscape, with foundational topics such as "cytotoxicity" and "genotoxicity" complemented by emerging themes like "machine learning," "nanoplastics," and "metabolomics." This progression indicates a shift from basic toxicological assessments to integrating advanced technologies and methodologies, reflecting the field's interdisciplinary nature. The thematic map further supports this by categorizing well-established topics as basic themes while highlighting the need for more integration of niche and emerging topics into broader frameworks. The absence of motor themes in the thematic map suggests a research gap in developing highly relevant, well-integrated topics that can drive the field forward.

The analysis of key contributors and sources demonstrates the collaborative nature of nanotoxicology research, with a high average of 6.25 co-authors per document and significant international co-authorship. Leading authors and journals play a critical role in shaping the discourse, yet the low number of single-authored documents indicates reliance on teamwork and interdisciplinary input. This collaboration extends to countries, where networks visualize strong partnerships, particularly between major contributors like the United States and China. However, the relatively smaller contributions from regions like Africa and South America

highlight the need for initiatives to foster global participation and equity in research efforts.

Bibliographic coupling and keyword clustering highlight the interconnectedness of research themes, with key documents and clusters forming the backbone of the field. Topics such as "nanotoxicology," "silver nanoparticles," and "risk assessment" dominate, but the lack of connectivity between niche and broader themes highlights an opportunity for integrating specialized knowledge into a unified framework. This gap could be addressed through targeted funding for multidisciplinary research and the establishment of standardized methodologies for assessing nanoparticle toxicity across diverse applications.

The practical implications of these findings are significant. Policymakers and researchers must prioritize emerging concerns like environmental impacts, regulatory frameworks, and advanced diagnostic techniques such as "proteomics" and "metabolomics." Furthermore, the growing relevance of topics like "machine learning" suggests a need to incorporate computational approaches to predict and mitigate nanotoxicity. By addressing research gaps and fostering global collaboration, the field can ensure safer and more sustainable applications of nanotechnology, benefiting both society and the environment.

5. Conclusion

The bibliometric analysis of nanotoxicology highlights the rapid growth and interdisciplinary nature of the field, driven by increasing concerns over the impacts of nanomaterials on health and the environment. The findings reveal strong contributions from leading countries like China and the United States but also underscore the need for broader participation from underrepresented regions to achieve a globally inclusive research landscape. Emerging topics such as "nanoplastics," "machine learning," and "metabolomics" signal a shift towards advanced, data-driven methodologies, emphasizing the importance of innovation in addressing contemporary challenges. To advance the field, it is recommended that researchers prioritize integrating niche themes into broader frameworks to develop motor themes that can unify and propel the field forward. Efforts should also focus on fostering international collaborations, particularly between established research hubs and emerging regions, to share knowledge and resources effectively. Additionally, policymakers and funding agencies must support research initiatives addressing regulatory, environmental, and societal implications, ensuring the safe and sustainable application of nanotechnology. Strengthening the connection between fundamental toxicological studies and practical applications will help bridge existing gaps, offering solutions to both global health and environmental concerns. Overall, this analysis provides a roadmap for future research, encouraging interdisciplinary approaches and global partnerships to drive impactful advancements in nanotoxicology.

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