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Review Article

Mapping Global Research on Nanoparticle-Induced Oxidative Stress: A Bibliometric Approach (2000–2025)

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ABSTRACT

Background: This study provides a bibliometric overview of global research on the toxicological impacts of nanoparticles (NPs), with a particular focus on oxidative stress in environmental systems.

Methods: A total of 1507 documents published between 2000 and 2025 were retrieved from the Scopus database. Using Bibliometrix and VOSviewer, we analysed leading countries and authors, keyword co-occurrence, publication trends, and research gaps.

Results: Scientific output in this field has increased rapidly, with an average annual growth rate of 24.15% and a mean of 41.98 citations per article, indicating substantial scholarly impact. Oxidative stress emerged as the central theme, with particular emphasis on the roles of reactive oxygen species (ROS) and antioxidant defense systems.

Conclusion: Despite the field's strong growth, important gaps remain, including limited work on chronic exposure, interactions between NPs and other pollutants, and effects on non-model organisms.

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Introduction

Nanoparticles (NPs) are generally defined as particles with sizes ranging from 1 to 100 nanometers. These particles have physicochemical properties that are increasingly exploited across many fields, such as food technology, environmental remediation, and drug delivery (Habib et al., 2024).

Because of their small size and surface reactivity, NPs can cross biological barriers, interact directly with cellular structures, and trigger oxidative stress by producing reactive oxygen species (ROS). This may contribute to inflammation, DNA damage, and, in some cases, carcinogenic processes (Roy et al., 2023). Furthermore, these small particles can persist in the environment, move along food chains, and pose long-term risks to ecosystems and human health (Madkour, 2020; Horie & Tabei, 2021; Jampílek & Kráľová, 2024).

Given the rapid growth of the literature on this topic, it is important to analyse existing knowledge. Bibliometric analysis offers a useful way to map a research field by highlighting influential authors, institutions, and journals, as well as research trends and gaps. By applying quantitative methods to academic publications, this approach helps to describe how a field has evolved and to clarify its current structure (Kumar, 2025).

In this context, the present study provides an overview of global research on NP toxicity over the last 25 years, with a particular focus on oxidative stress in environmental systems. Using data from the Scopus database and visualization tools such as VOSviewer and Biblioshiny, we examine publication trends, citation patterns, international collaboration, and keyword co-occurrence networks to outline the main research directions and identify gaps that could be addressed in future works.

Materials and Methods

All bibliographic data were retrieved from the Scopus database on July 2025. The query was designed to cover a broad spectrum of research on NP-induced environmental toxicity related to oxidative stress by searching titles, abstracts, and keywords, using the following search string: ("nanoparticle*" OR "nanoparticle*" OR "nanomaterial*" OR "nanomaterial*" OR "engineered nanoparticle*") AND ("environmental toxicity" OR "ecotoxicity" OR "ecotoxicological" OR "toxic effect*" OR "environmental impact*" OR "toxicity assessment") AND ("oxidative stress").

Only research articles that were published in English between 2000 and 2025 were considered for inclusion. Also, the subject area was limited to: Environmental Science; Biochemistry, Genetics and Molecular Biology; Pharmacology, Toxicology and Pharmaceutics; Medicine; Immunology and Microbiology; Health Professions; and finally, Neuroscience.

The extracted data were exported in CSV and BibTeX formats. The bibliometric analysis and network visualization were performed using the Bibliometrix R package (version 4.5.1 via the Biblioshiny interface) and VOSviewer software.

Results

Although the bibliometric search covered the period from 2000 onward, the first relevant Scopus-indexed article on nanoparticle-induced oxidative stress appeared only in 2004. In that study, Xia et al. (2004) showed that diesel particles bearing quinones and PAHs caused mitochondrial dysfunction and oxidative stress. In contrast, inert polystyrene nanoparticles did not, highlighting the key role of adsorbed chemicals in toxicity. From 2004 to 2025, 1,507 documents published in 332 distinct journals were identified, illustrating the rapid growth of research in this area.

Temporal Evolution of Scientific Production

Scientific production over time reveals an exponential growth (Figure 1), with an average annual growth rate of 24.15%. The increase becomes especially marked after 2012, and more than half of all articles (51.62%) were published between 2020 and 2024, which confirms that this topic has attracted strong recent interest.

The drop seen in 2025 is likely not a real decline in research activity, but rather a consequence of delays in indexing and record updates in Scopus, a common limitation in bibliometric analyses conducted during the year.

Disciplinary Distribution of Research

The field's fundamentally interdisciplinary nature is confirmed by the distribution of publications (Figure 2). Environmental Science is the dominant field, with 1,000 documents, accounting for 32.2% of the total corpus. It is followed by Pharmacology, Toxicology, and Pharmaceutics (15.3%), Biochemistry, Genetics,

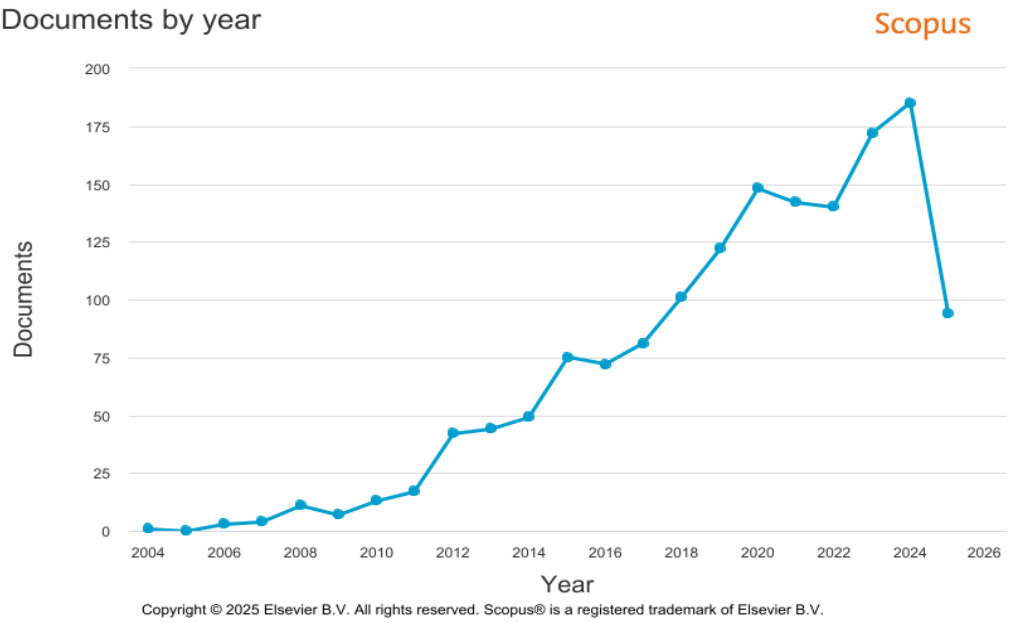

Figure 1. Growth of annual scientific production from 2000 to 2025.

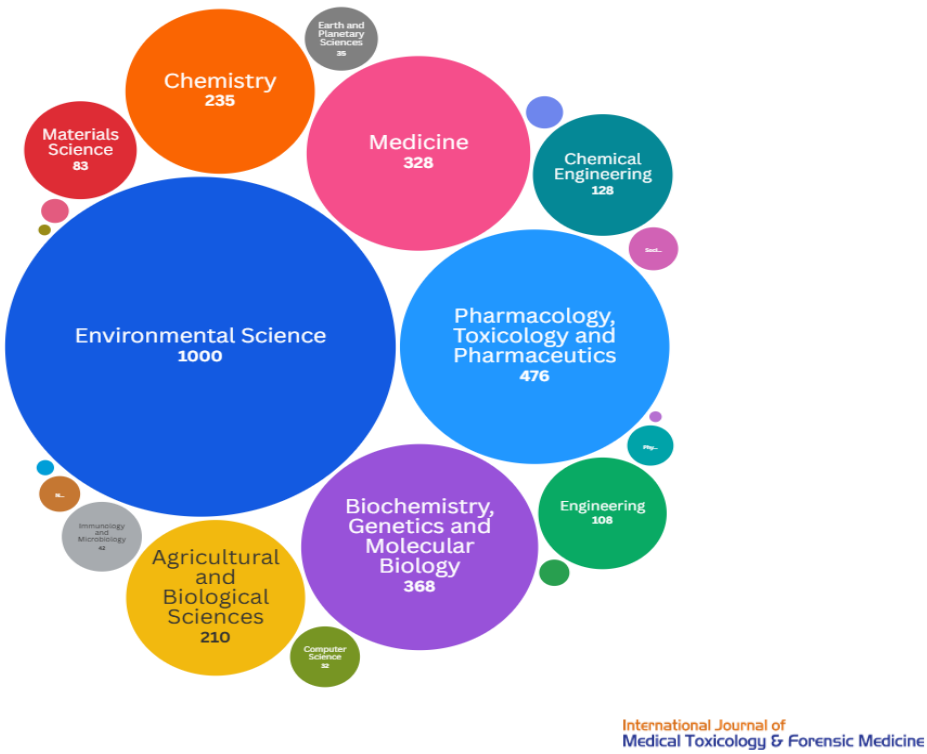

Figure 2. Bubble chart of research fields.

and Molecular Biology (11.8%), and Medicine (10.5%). Many papers are assigned to more than one field, so the total percentage exceeds 100%.

Most Influential Scientific Journals

The 1507 documents retrieved were published in approximately 332 distinct Scopus-indexed journals. Nevertheless, only 58 journals have published five or more documents.

Table 1 presents the most influential journals based on the number of publications, citations, and co-citation strength. *Science of the Total Environment* ranks first, with 112 articles and 5,701 citations, indicating its central role in the field. *Aquatic Toxicology* has fewer papers (70) but a high citation count (4,407), corresponding to an average of about 63 citations per article, which underlines its strong impact.

Table 1. The top ten influential scientific journals in the research domain.

Source	Documents	Citations	Total link strength
Aquatic Toxicology	70	4407	275
Science of the Total Environment	112	5701	240
Ecotoxicology and Environmental Safety	90	3370	151
Chemosphere	79	3102	146
Environmental Science and Pollution Research	59	1105	117
Environmental Science and Technology	41	4135	115
Environmental Pollution	66	4338	114
Journal of Hazardous Materials	63	2363	86
Marine Environmental Research	14	1112	85
Comparative Biochemistry and Physiology	26	633	76

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Most Influential Documents

Of the 1,507 articles identified, 1,022 had been cited at least ten times. Overall, each article has received about 42 citations, indicating substantial visibility and impact. Moreover, 28.33% of the publications involved international collaboration, underlining the global nature of research on nanoparticle-induced oxidative stress. Table 2 summarizes the most highly cited papers worldwide on this topic. Using TC together with TC/year and normalized TC provides a more balanced view of impact, distinguishing historically foundational contributions from recent high-momentum papers.

The most influential article is Karlsson et al (2008), which reported that nanoparticle-induced toxicity varies markedly by material in human lung epithelial

Table 2. Summary of the most globally cited articles on the topic, including: Digital Object Identifier (DOI), Total Citations (TC), Citations Per Year (TC per Year), and Normalized Citation Count (Normalized TC).

Paper	DOI	TC	TC per Year	Normalized TC
Karlsson HL, 2008, *CHEM RES TOXICOL*	10.1021/tx800064j	1296	72,00	5,19
Federici G, 2007, *AQUATIC TOXICOL*	10.1016/j.aquatox.2007.07.009	726	38,21	1,71
Akhavan O, 2012, *BIOMATERIALS*	10.1016/j.biomaterials.2012.07.040	713	50,93	6,38
Jeng HA, 2006, *J ENVIRON SCI HEALTH PART A TOXIC HAZARD SUBST ENVIRON ENG*	10.1080/10934520600966177	709	35,45	1,33
Kawata K, 2009, *ENVIRON SCI TECHNOL*	10.1021/es900754q	630	37,06	1,77
Chen Q, 2017, *SCI TOTAL ENVIRON*	10.1016/j.scitotenv.2017.01.156	587	65,22	11,61
Song W, 2010, *TOXICOL LETT*	10.1016/j.toxlet.2010.10.003	584	36,50	2,55
Kasemets K, 2009, *TOXICOL VITRO*	10.1016/j.tiv.2009.05.015	566	33,29	1,59
Xiong D, 2011, *SCI TOTAL ENVIRON*	10.1016/j.scitotenv.2011.01.015	521	34,73	3,07
Lin W, 2006, *INT J TOXICOL*	10.1080/10915810600959543	503	25,15	0,94

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cells, with CuO nanoparticles showing the strongest effects on cytotoxicity and DNA damage and also causing oxidative lesions and a near-significant increase in intracellular ROS; ZnO reduced cell viability and induced DNA damage, TiO_2 primarily induced DNA damage, several iron oxides showed low or no toxicity, $CuZnFe_2O_4$ was relatively potent in inducing DNA lesions. Carbon nanotubes induced cytotoxicity and DNA damage even at the lowest tested dose, effects not explained by released metal ions or soluble metal impurities.

Authors and Collaboration

In total, 6,146 authors contributed to the publications indexed in Scopus during the study period. Among them, 71 researchers authored ten or more articles, with Wang J being the most prolific, with 58 articles. However, Mukherjee A emerges as the leading individual contributor when author contributions are weighted using a fractionalized score. Figure 3 helps distinguish between simple participation in large multi-author teams and more substantial intellectual involvement.

Geographical Distribution and Research Collaborations

China is the leading contributor, with 491 publications (32.58% of all documents), followed by India, Egypt, Iran, and the United States (Figure 4[a]). Analysis of corresponding authors' affiliations shows that China has a high proportion of single-country publications (SCPs), reflecting strong national research capacity but limited international collaboration. By contrast, countries such as India, Egypt, and several European nations have a more balanced mix of SCP and multiple-country publications (MCP), indicating closer integration into international research networks (Figure 4[b]).

Keywords and Research Trends

Co-occurrence analysis of author keywords identified 3,495 distinct terms; 212 of them have at least 5 co-occurrences. The VOSviewer map (Figure 5) shows the conceptual structure of the field, with "oxidative stress" at the center, closely connected to terms such as "reactive oxygen species (ROS)", "cytotoxicity", "apoptosis", and "gene expression".

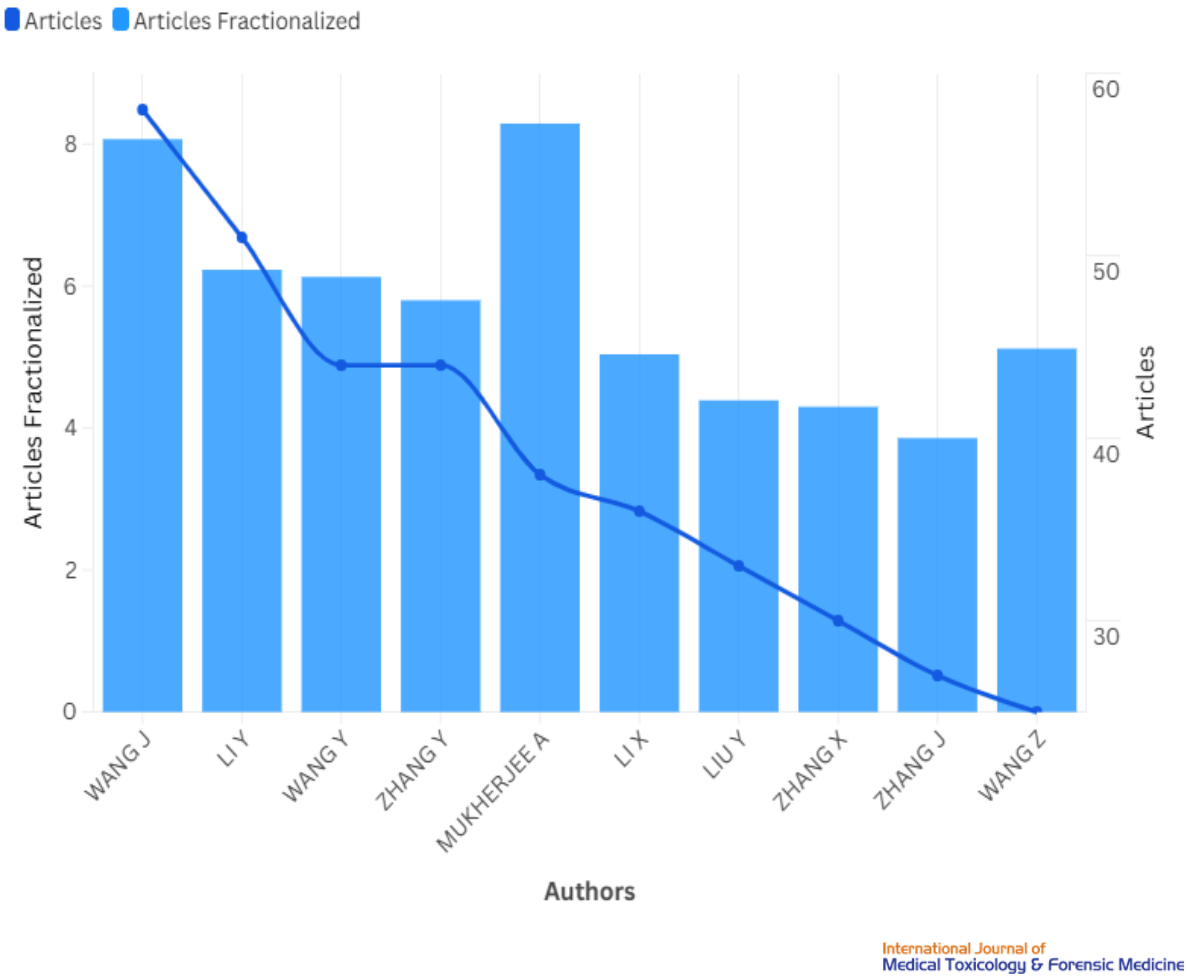

Figure 3. Top 10 Authors by total publications and fractionalized score.

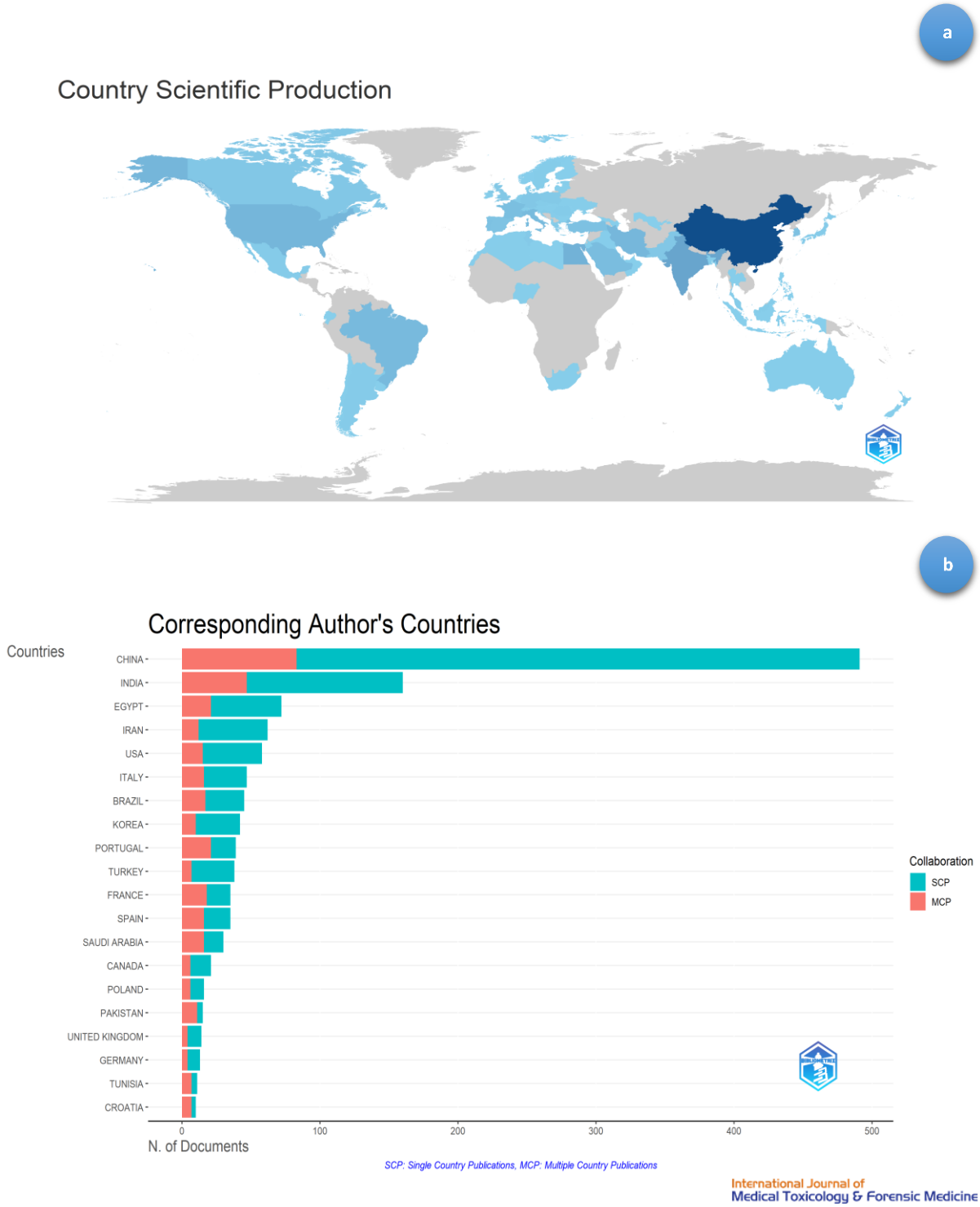

Figure 4. Geographical Distribution. World map of scientific production (a). Scientific contributions by country based on corresponding authors (b): SCP (Single Country Publications); MCP (Multiple Country Publications).

The keywords are organized into 11 thematic clusters. One major cluster group term related to the toxic effects of NPs and other contaminants in aquatic organisms, including biomarkers, molecular mechanisms, bioaccumulation, biotransformation, and risk assessment for human and environmental health. Research in this area is primarily focused on three themes: the biochemical mechanisms of toxicity, characterization of NPs, and their effects in animal models.

Furthermore, the overlay visualization provided the results illustrated in Figure 6. The map highlights more recent topics such as “nanoplastics”, “transcriptomics”, “chronic exposure”, and “combined toxicity”, pointing to current and emerging research fronts.

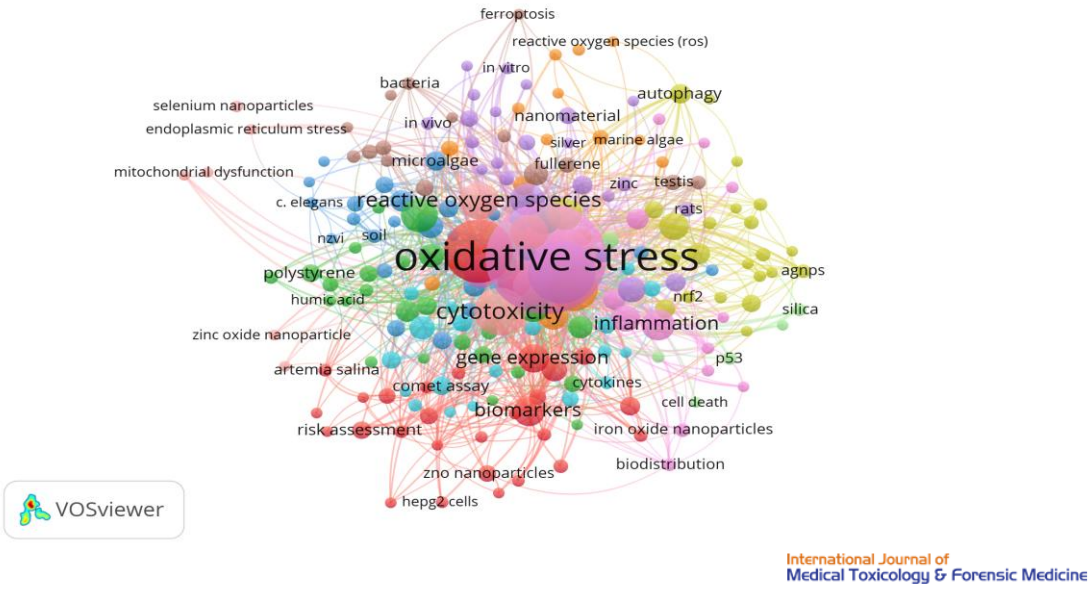

Figure 5. Keyword co-occurrence mapping in studies on NP toxicity. Each node represents a keyword, with its size indicating the frequency of occurrence. The proximity between nodes reflects their co-occurrence within the same articles. Colors distinguish thematic clusters (groups of related keywords), thereby revealing the main research axes.

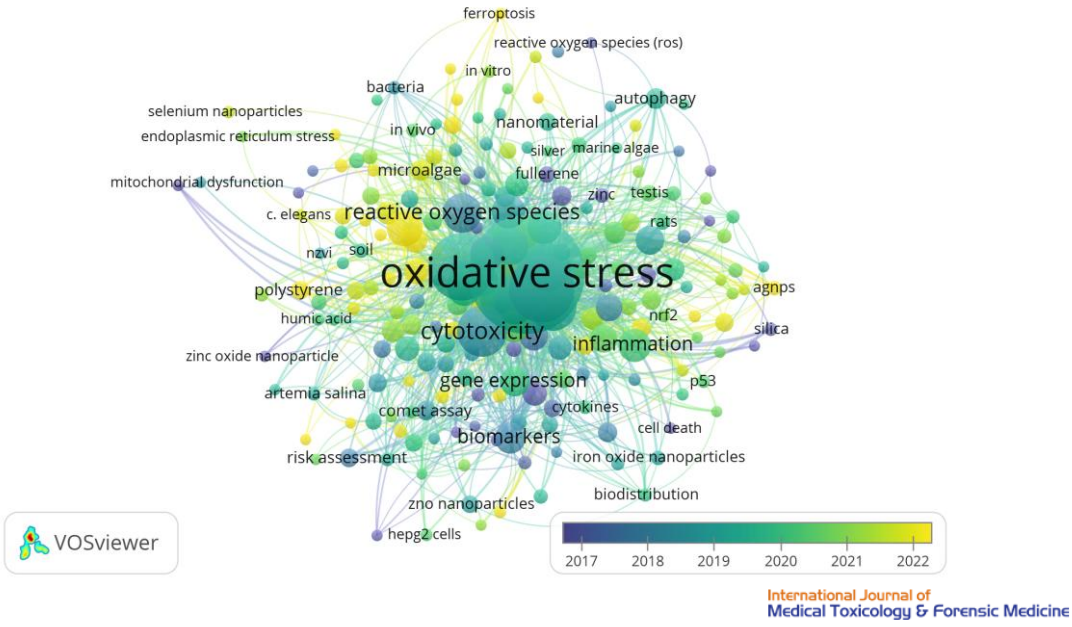

Figure 6. Temporal evolution of keywords in NP toxicity research (Overlay Visualization). Each node represents a keyword; its size reflects its frequency of occurrence, and its color indicates the average year of publication associated with that keyword (see the timeline scale at the bottom). Connections between nodes represent co-occurrences within the same scientific articles. Keywords in blue/purple correspond to earlier research (2017–2018), while those in yellow/light green highlight more recent topics (2021–2022).

Despite the large number of publications, our analysis highlights clear gaps and practical priorities for future work. Most studies still assess a single nanomaterial. Yet real exposure involves mixtures of substances, including microplastics, pesticides, and heavy metals. These interactions may be additive, synergistic, or antagonistic. The literature is also biased toward a few model species and mostly aquatic settings. Terrestrial ecosystems, soil microbiomes, and non-model organisms remain underrepresented. In addition, chronic exposure is still insufficiently studied. Short-term designs and unrealistically high concentrations are common. Long-term studies at environmentally relevant doses are needed, including multigenerational endpoints.

These gaps matter for regulation and environmental risk assessment. They weaken the evidence base needed for decisions under realistic

conditions. International frameworks highlight the same needs: OECD promotes harmonised approaches to hazard, exposure, and risk assessment, with nano-specific adaptations (OECD, 2022). In Europe, REACH requirements for nanoforms and ECHA guidance stress robust nanoform characterisation and fit-for-purpose hazard data (European Union, 2018). ISO guidance also emphasises standardised physicochemical characterisation to improve comparability across studies (ISO, 2024). Overall, our mapping helps identify where method development, standardised testing, and monitoring are most urgently needed

Discussion

This bibliometric analysis provides a structured overview of the evolution of research on nanoparticle-induced oxidative stress over the past two decades. The marked increase in publications, particularly after 2012, reflects the growing importance of nanotoxicology within environmental and health-related research. The distribution of publications across leading journals in environmental science and toxicology indicates that this field has been mainly developed within ecotoxicological and mechanistic frameworks, with oxidative stress consistently identified as a key axis for interpreting nanoparticle toxicity.

The bibliometric mapping also shows that the field is conceptually organized around well-established toxicological mechanisms, notably ROS generation, cytotoxicity, apoptosis, and oxidative damage [4, 7, 8, 13, 20]. At the same time, the strong contribution of countries such as China and the citation impact of highly influential publications illustrate the global consolidation of this research domain. These findings suggest that the literature has moved beyond exploratory reporting and now rests on a more coherent mechanistic foundation.

Another important observation is the progressive diversification of research themes. The growing visibility of topics such as nanoplastics, chronic exposure, transcriptomics, and combined toxicity indicates that current research is increasingly addressing more complex and realistic exposure conditions. This shift suggests a methodological maturation of the field, with greater attention to exposure complexity and biological response pathways. However, the bibliometric profile also points to persistent imbalances, including the limited representation of terrestrial systems, non-model species, and long-term study designs. Taken together, these patterns support the need for better methodological harmonization and stronger risk-assessment frameworks in nanotoxicology [9–11, 17].

Conclusion

In summary, this bibliometric study demonstrates that research on nanoparticle-induced oxidative stress has grown substantially and has become increasingly structured over time. The field is characterized by a strong mechanistic focus on oxidative stress pathways and by the emergence of newer themes that reflect more realistic environmental and biological exposure scenarios.

By identifying major publication trends, influential contributors, and evolving thematic priorities, this analysis helps clarify the current organization of knowledge in this area. It also highlights research domains that remain insufficiently explored, especially those involving broader biological models and longer exposure frameworks. Overall, this mapping may support future studies aimed at improving the scientific basis of nanotoxicological evaluation and the development of safer and more sustainable nanotechnology applications.

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Conflicts of Interest

The authors report there are no competing interests to declare.

Declaration of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the authors used artificial intelligence (ChatGPT 5.1) to enhance the linguistic quality of the text.

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