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Mapping research frontiers in microplastics-induced oxidative stress: a bibliometric analysis (2010–2024)

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Introduction: Microplastics exposure is increasingly recognized as a significant contributor to oxidative stress, prompting growing concerns about potential human health impacts. This study aimed to systematically analyze emerging research trends and key thematic areas related to oxidative stress induced by microplastics, providing insights that could inform effective antioxidant-based interventions.

Methods: A total of 1,820 relevant articles published between 2010 and 2024 were retrieved from the Web of Science Core Collection. Bibliometric techniques, including Latent Dirichlet Allocation (LDA), keyword co-occurrence analysis, and temporal regression modeling, were employed to analyze thematic structures, keyword relationships, and research development patterns.

Results: Analysis revealed a notable increase in research volume over the study period, particularly highlighting health risk assessments and molecular mechanisms as focal points. Oxidative stress was identified as a central mediator linking inflammation, gut microbiota alterations, and apoptotic pathways. Clustering analyses demonstrated significant interdisciplinary connections, underscoring complex interactions across multiple biological systems. Additionally, temporal analysis indicated a recent surge in studies emphasizing health risk evaluations and potential antioxidant interventions.

Discussion: The findings emphasize oxidative stress as a crucial mechanism in microplastics-induced toxicity, suggesting dietary antioxidants, such as zinc and N-acetylcysteine, could mitigate associated health risks. This study provides valuable perspectives to guide future research directions and public health strategies aimed at addressing microplastics exposure.

KEYWORDS

microplastics exposure, oxidative stress mechanisms, health risk evaluation, antioxidant strategies, environmental toxicology, bibliometric mapping

1 Introduction

Plastic products, prized for their low cost and durability, have become indispensable in modern production and consumption (Kwesiga, 2018; Naser et al., 2021). However, the pervasive use of plastics has precipitated an environmental crisis (Black et al., 2019; Jawaid et al., 2023), with global plastic consumption predicted to exceed 800 million tons by 2050 (Tan et al., 2024). The degradation of plastic waste through physical, chemical, and biological processes generates microplastics (MPs, 1–5 mm) and nanoplastics (NPs, 1–100 nm), posing significant threats to ecosystems and human health (Jahnke et al., 2017). Microplastics have been detected across the marine environment, freshwater systems, and even in remote regions like the Arctic (Kutralam-Muniasamy et al., 2023). Alarmingly, recent studies have also identified nanoplastics in human tissues, including the placenta, breast milk, blood, and kidneys, highlighting their pervasive presence and potential toxicity (Malafaia and Barceló, 2023).

The environmental and health risks posed by microplastics have become an urgent global concern. Microplastics disrupt marine ecosystems by altering food webs and biogeochemical cycles, and ingestion of microplastics by marine organisms leads to bioaccumulation and biomagnification (Ricciardi, et al., 2021; Yu, et al., 2021; Li, et al., 2023). From a human health perspective, nanoplastics penetrate cells through mechanisms such as endocytosis, phagocytosis, or passive diffusion, triggering oxidative stress—a key driver of their toxicological effects (Khan and Jia, 2023). Oxidative stress occurs when the production of reactive oxygen species (ROS) exceeds the neutralizing capacity of the body's antioxidant defenses (Albano et al., 2022; Shchulkin et al., 2024; Hong et al., 2024), resulting in damage to DNA, RNA, proteins, and lipids (Assi, 2017; Goffart et al., 2021; Lichtenberg et al., 2023). This condition has been linked to a variety of health outcomes, including aging (Jomová et al., 2023), tumorigenesis (Acevedo-León et al., 2022), and neurological disorders (Formichi et al., 2012; Wei and Xu, 2023). Although the effects of microplastics on human health play a key role, the exact mechanisms by which microplastics induce oxidative stress are still not fully understood, especially in the context of long-term exposure and multisystem interactions.

Recent advances in bibliometric analysis provide a powerful tool for synthesizing research trends and identifying knowledge gaps in emerging fields. By systematically mapping the research landscape of microplastics-induced oxidative stress, bibliometric methods can provide a deeper understanding of research hotspots and topic evolution (Liu, et al., 2024). Techniques such as latent Dirichlet assignment (LDA) modeling and keyword co-occurrence analysis reveal temporal trends and thematic connections, providing a comprehensive overview of developments in the field. These approaches also highlight key gaps, such as the limited exploration of the mechanisms by which nanoplastics affect human health, and the underrepresentation of long-term ecological impacts in current studies.

This study aims to provide a systematic analysis of the research landscape on oxidative stress induced by microplastics exposure, focusing on publication trends, keyword associations, and thematic evolution from 2010 to 2024. By identifying research hotspots and future directions, this work offers valuable insights for addressing the health risks associated with microplastics and for shaping interdisciplinary research, policy development, and innovative mitigation strategies. Additionally, the findings provide a theoretical basis for formulating effective antioxidant interventions, which hold promise for reducing the adverse health impacts of microplastics exposure. This research not only contributes to the field of environmental toxicology but also informs policies aimed at reducing plastic production and enhancing waste management.

Unlike previous bibliometric reviews that broadly assessed microplastics toxicity, this study specifically focuses on oxidative stress mechanisms and their implications for human health. By employing advanced topic modeling and trend analysis, we provide a refined thematic structure and highlight emerging research gaps that warrant further exploration.

2 Data and methods

2.1 Data sources and search strategy

The data for this study were obtained from the Web of Science Core Collection databases, specifically the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI), covering publications from 1 January 2010, to 31 October 2024. We included articles of types "article" and "review article," using the search strategy: TS= (Microplastics OR Nanoplastics) AND (Oxidative Stress). After removing duplicates and performing manual screening, a total of 1,820 studies directly related to microplastics-induced oxidative stress were selected for analysis.

The explicit inclusion and exclusion criteria to ensure relevance and scientific rigor were as follows:

Inclusion criteria: 1) Studies published as original research articles or review articles. 2) Studies explicitly examining oxidative stress as a key research outcome following expoure to microplastics or nanoplastics. 3) Studies conducted between 1 January 2010, and 31 October 2024.

Exclusion criteria: 1) Studies not directly investigating oxidative stress as a primary endpoint. 2) Studies exclusively investigating macroplastics or plastic additives without specific reference to microplastics or nanoplastics. 3) Environmental exposure assessments not directly addressing oxidative stress responses. 4) Conference abstracts, editorials, letters, books, or other non-peer-reviewed publications.

2.2 Analytical methods

Three complementary analytical approaches were employed to investigate research hotspots and trends in Microplastics-induced oxidative stress.

2.2.1 LDA topic modeling analysis

Latent Dirichlet Allocation (LDA) modeling was applied to the titles, abstracts, and keywords of the selected articles. This machine-learning-based method systematically classifies textual data into latent themes, enabling the identification of major research topics and their temporal evolution (Chen and Gui, 2021). The LDA modeling process provided insights into the thematic structure and dynamics of the field, highlighting emerging areas of interest and evolving trends (Zhang et al., 2023).

2.2.2 Keyword co-occurrence analysis

Keyword co-occurrence analysis was performed using VOSviewer software. This method visualized co-occurrence networks, revealing high-frequency keywords and their associations. The co-occurrence network helped to identify the structural relationships between keywords and confirmed the

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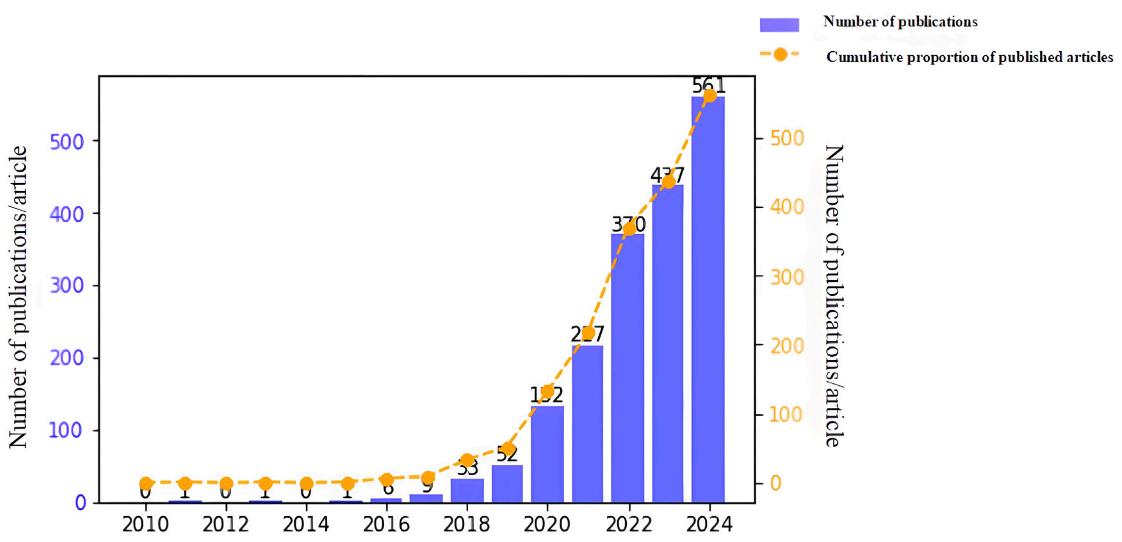

FIGURE 1
Global publication trends in microplastics-induced oxidative stress research from 2010 to 2024, based on articles indexed in the Web of Science Core Collection.

thematic clusters identified through LDA modeling. This analysis offered a deeper understanding of research interconnections and the field's evolving landscape (Saputro et al., 2023).

2.2.3 Linear regression trend analysis

Temporal trends were analyzed using a linear regression model, based on the themes identified by LDA modeling. Five-time intervals were defined for the analysis: 2010–2012, 2013–2015, 2016–2018, 2019–2021, and 2022–2024. The time intervals served as the independent variable, while publication volume for each theme was the dependent variable. Themes with statistically significant positive regression coefficients ($p < 0.05$) were classified as hot topics, reflecting increasing attention. Conversely, themes with negative coefficients or insignificant results were deemed cold topics, indicating waning interest. This approach provided insights into the dynamic trajectory of Microplastics and oxidative stress research over time.

2.3 Data management and statistical analysis

EndNote software was utilized for literature management tasks, including deduplication, classification, and archiving. Python programming was employed for quantitative analyses, including publication trend analysis, LDA topic modeling, and linear regression modeling. VOSviewer software was used to generate keyword co-occurrence maps, offering visual insights into the structural patterns and interconnections within the field.

The integration of these analytical methods produced a comprehensive overview of research hotspots, emerging trends, and thematic dynamics in Microplastics-induced oxidative stress. By combining quantitative statistical results with detailed visualizations, this study provided a robust framework for understanding the development and future directions of this rapidly evolving field.

3 Results

3.1 Global publication trends in microplastics-induced oxidative stress research

Figure 1 illustrates the annual publication trends and cumulative proportions of global research on Microplastics-induced oxidative stress from 2010 to 2024. During the initial phase (2010–2018), research activity in this field was relatively sparse, with fewer than 50 articles published annually. This limited output suggests that the topic was in its nascent stages, receiving minimal attention from the scientific community at the time.

A significant surge in research activity has been evident since 2019, with particularly rapid growth observed after 2020. Annual publication counts increased markedly from 120 in 2020 to a projected 561 by the end of 2024. The cumulative proportion of publications (indicated by the orange dashed line in Figure 1) demonstrates that over 75% of all articles in this domain were published after 2020. This exponential growth underscores a sharp increase in global research interest, driven by heightened awareness of Microplastics pollution and its potential health impacts.

The observed trend highlights the growing recognition of oxidative stress as a central toxicological mechanism in Microplastics exposure, which has spurred an urgent need for further investigation. This surge in publications aligns with broader efforts to address pressing environmental and health challenges associated with Microplastics. The dramatic increase in research output since 2020 reflects not only advancements in detection technologies and methodological frameworks but also the prioritization of this topic in academic and policy-making circles. These findings underscore the critical importance of Microplastics-induced oxidative stress research in shaping future intervention strategies and mitigating associated risks.

To provide a comprehensive understanding of the identified research trends, we synthesized the relationships among the key

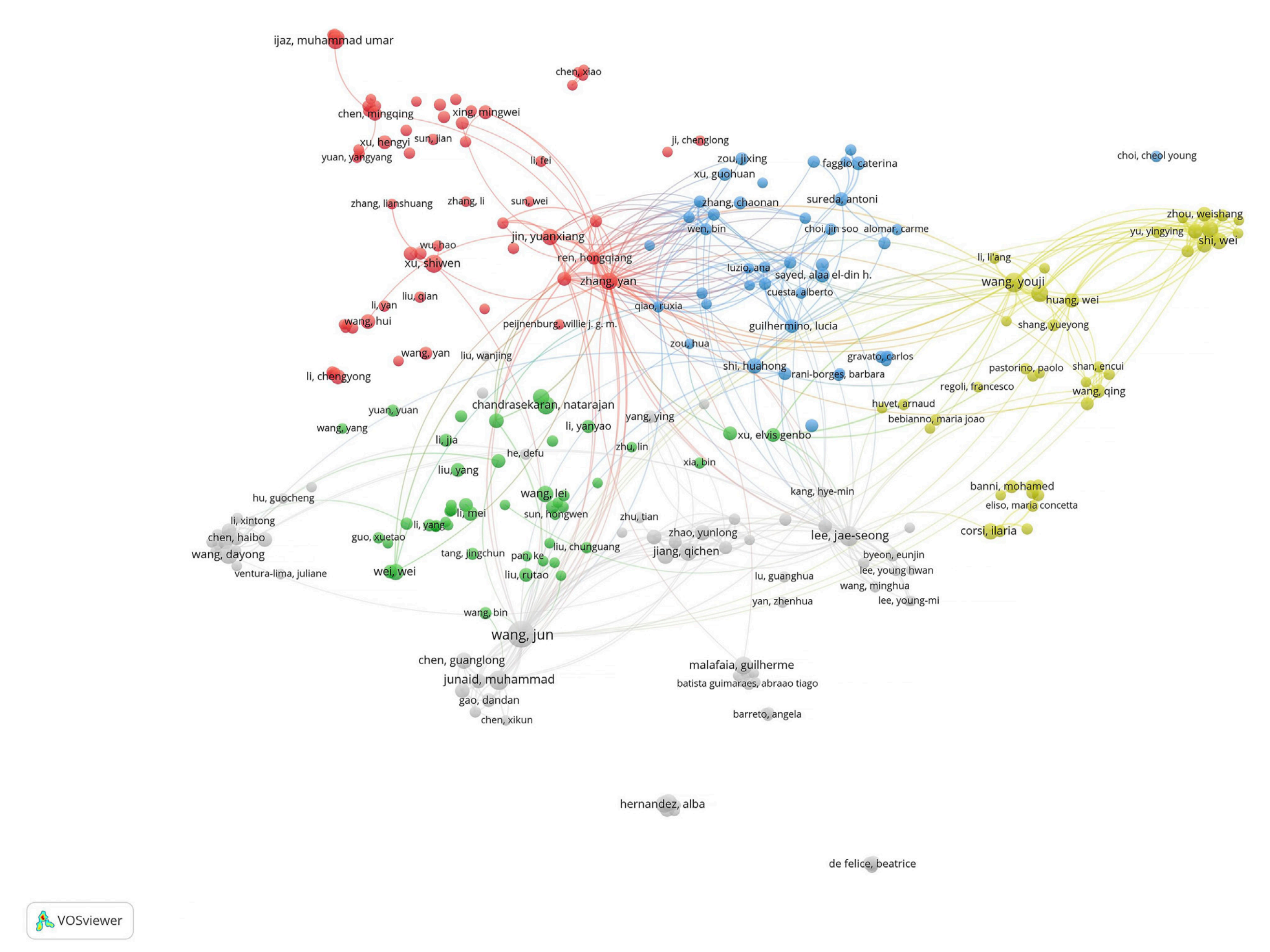

FIGURE 2
Academic citation network of highly cited authors in the field of microplastics-induced oxidative stress (2010 -2024), illustrating key contributors and collaborative clusters.

themes. The integration of molecular mechanism studies (Topic 3) with health risk assessments (Topic 5) reveals that oxidative stress acts as a crucial intermediary linking microplastics exposure to adverse biological outcomes. Specifically, molecular-level investigations provide mechanistic insights into how oxidative stress influences cellular apoptosis, inflammation, and immune dysregulation, while health risk assessments contextualize these findings in terms of human disease outcomes, including metabolic disorders and systemic toxicity. This integration underscores the necessity of a multidisciplinary approach that bridges molecular toxicology with epidemiological research to develop effective mitigation strategies and policy interventions.

3.2 Academic citation network of highly cited authors in microplastics research

Figure 2 provides a panoramic view illustrating the academic citation network of highly cited authors in the microplastics research field. This visualization facilitates a deeper understanding of author relationships and influence patterns within this research area. Two notable characteristics emerge clearly from Figure 2: Firstly, the central region of the network highlights authors with substantial citation counts. These individuals often hold significant scholarly influence, serving as leading figures or pioneers within the microplastics research domain. Secondly, the peripheral areas showcase emerging scholars whose citation counts are relatively lower. Although their immediate impact is modest, these emerging researchers represent future potential and growth within the field.

Moreover, Figure 2 reveals distinct author clusters reflecting interdisciplinary research trends, demonstrating a clear intersection among various scientific disciplines. The presence of these clusters indicates specialized research areas and highlights interdisciplinary collaboration, as well as areas of particular research depth and focus. Analyzing these clusters helps identify current research priorities and promising future directions within microplastics research.

3.3 Major research themes and trends in microplastics-induced oxidative stress

The Latent Dirichlet Allocation (LDA) model identified eight primary research themes in publications on Microplastics-induced

TABLE 1 Eight research themes identified through LDA modeling in the field of Microplastics-induced oxidative stress research (2010–2024).

Theme	Keywords	Core content	Number of publications	Proportion (%)	Analysis
Topic 1	Plastic, fish, freshwater, response, pollution, particle, health, marine, aquatic, ingestion, water, polyethylene, environment, accumulation, debris	Explores the migration and accumulation of microplastics in freshwater and marine ecosystems, focusing on their oxidative stress-mediated impacts on fish and aquatic ecosystems	315	17.31	This theme represents a primary research focus in the field, reflecting growing concerns about microplastics pollution and its impacts on aquatic ecosystems
Topic 2	Cell, mouse, metabolism, gut, microbiota, fish, accumulation, damage, liver, mitochondrial, apoptosis, human, particle, zebrafish, intestinal	Investigates the effects of microplastics on gut microbiota alterations and their subsequent impacts on metabolic health, mitochondrial function, and inflammatory responses	282	15.49	Microplastics are closely associated with human health, particularly in relation to metabolic disorders and alterations in gut microbiota
Topic 3	Response, zebrafish, fish, system, cell, gene, antioxidant, growth, combined, inflammation, pollution, mechanism, carp, pathway, damage	Examines cellular-level responses of organisms, such as fish, to microplastic exposure, focusing on oxidative stress and antioxidant defense mechanisms	249	13.68	Focuses on molecular-level responses, providing critical insights into the mechanisms underlying microplastic toxicity
Topic 4	Response, mussel, earthworm, biomarkers, soil, cadmium, pollution, accumulation, eisenia, pollutant, mytilus, polyethylene, combined, biomarker, antioxidant	Explores the effects of microplastic-induced soil pollution on indicator species such as earthworms and mussels, emphasizing their role as biomarkers of ecological health	229	12.58	Reflects the expanding focus of research from aquatic to soil ecosystems, highlighting the synergistic effects of microplastics on ecological health
Topic 5	Human, response, growth, cell, health, impact, antioxidant, micro, soil, sludge, plant, microbial, particle, plastic, mechanism	Analyzes the direct and indirect health risks of microplastics on humans, focusing on oxidative stress and immune responses	195	10.71	Directly associated with human health, this theme represents a high-value direction with significant application potential in the field
Topic 6	Acid, combined, plastic, growth, particle, liver, pathway, gut, size, freshwater, zebrafish, water, substance, mechanism, aeruginosa	Investigates the toxic effects of microplastic pollutants on fish organs, including the liver, gut, and other tissues	187	10.27	Advances toxicological research at the aquatic ecosystem level, providing deeper insights into microplastic-induced organ toxicity
Topic 7	Zebrafish, elegans, *caenorhabditis*, intestinal, barrier, particle, microbiota, damage, nanopolystyrene, inflammation, reproductive, neurotoxicity, gut, apoptosis, pathway	Examines the impacts of Microplasticss on aquatic organisms, focusing on inflammation, neurotoxicity, and reproductive health risks	184	10.11	Highlights the toxic mechanisms of Microplasticss, providing a basis for refining risk assessments of nanomaterials
Topic 8	Response, particle, cell, plastic, mechanism, ingestion, water, apoptosis, zebrafish, behavior, damage, expression, environmental, impact, health	Explores the multifaceted impacts of microplastic exposure on behavior and cellular functions	179	9.84	Research on behavioral changes remains limited, indicating significant potential for further exploration

oxidative stress from 2010 to 2024 (Table 1). These themes are grouped into three broad categories: ecotoxicity, molecular mechanisms, and health risks, underscoring the multidisciplinary nature of this research field. Among these, Topic 2, Topic 3, and Topic 5 specifically address oxidative stress mechanisms, forming the central axis of research into Microplastics toxicity and its health implications.

3.3.1 Ecological impact (topic 1) and health risks (topic 2)

Topic 1 (Ecological Impact; 17.31%): This theme is the most prominent, focusing on the migration, accumulation, and ecotoxicity of Microplastics in freshwater and marine ecosystems. Studies emphasize the oxidative stress-induced effects of Microplastics on aquatic organisms, particularly fish, highlighting oxidative stress as a critical pathway driving ecosystem-level toxicity. These findings reveal the potential threat of Microplastics to aquatic biodiversity and ecosystem health, illustrating their far-reaching ecological consequences.

Topic 2 (Health Risks; 15.49%): This theme investigates the oxidative stress-related health risks of Microplastics exposure in humans. Research centers on key areas such as gut microbiota dysbiosis and metabolic disorders, with an increasing focus on chronic disease development linked to oxidative stress. The shift from ecological impacts to human health risks reflects growing recognition of the broader implications of Microplastics exposure, particularly its contribution to long-term health challenges.

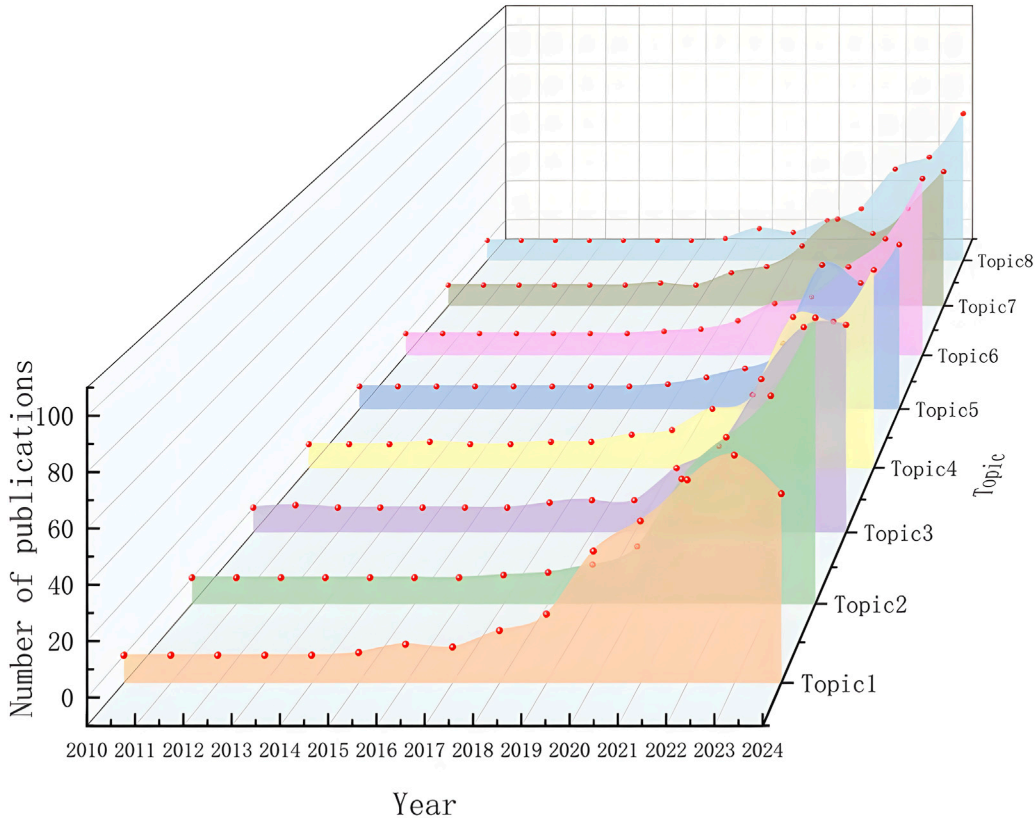

FIGURE 3
Publication trends of eight major research themes related to microplastics-induced oxidative stress from 2010 to 2024, derived from topic modeling analysis.

3.3.2 In-depth research on molecular mechanisms (topic 3 and topic 5)

Topic 3 (Molecular Mechanisms; 13.68%): This theme delves into the molecular basis of Microplastics toxicity, particularly the role of oxidative stress in inducing cellular damage and activating antioxidant defenses. Studies explore cellular responses in model organisms (e.g., fish), the regulatory roles of antioxidants, and the involvement of signaling pathways such as ROS-mediated mechanisms. These investigations provide critical insights into the fundamental biological processes underlying Microplastics-induced oxidative stress.

Topic 5 (Health and Immune Responses; 10.71%): Extending molecular research to health impacts, this theme emphasizes oxidative stress-induced immune responses. Studies highlight the interplay between oxidative stress and immune function, with a focus on the regulation of antioxidants and biomolecules. Findings suggest oxidative stress as a pivotal mediator linking Microplastics exposure to systemic health effects, including immune dysregulation and chronic inflammation. These results advance understanding of the systemic consequences of Microplastics exposure, providing a foundation for mitigating associated health risks.

3.3.3 Publication trends across research theme

Figure 3 depicts the publication trends of eight identified research themes in the field of Microplastics-induced oxidative stress between 2010 and 2024. The overall research activity in this domain has shown consistent growth, with a notable acceleration after 2019, underscoring the field's rapid development and increasing prominence in environmental and health sciences.

Topic 1 (Ecological Impacts) and Topic 2 (Gut Microbiota and Health Risks) consistently recorded high publication volumes, indicating sustained academic interest in the oxidative stress mechanisms underpinning ecosystem toxicity and human health impacts. These themes highlight the dual focus of research on the environmental and physiological consequences of Microplastics exposure.

Topic 3 (Molecular Mechanisms) and Topic 5 (Health Risk Assessment) reflect a deeper exploration of cellular and systemic toxicity mechanisms, with an emphasis on oxidative stress-induced immune dysregulation and biomolecular damage. These topics underscore the centrality of oxidative stress as a pivotal mechanism linking Microplastics exposure to adverse biological outcomes, providing a foundation for targeted mitigation strategies.

Emerging themes, including Topic 7 (Neurotoxicity and Reproductive Health) and Topic 8 (Behavioral Impacts), illustrate the expanding scope of research. These themes address the potential risks of Microplastics exposure on neurotoxicity, reproductive health, and behavioral alterations, marking a shift towards multidimensional evaluations of health risks. The exploration of such novel areas reflects growing recognition of the complex and systemic nature of Microplastics-induced oxidative stress, paving

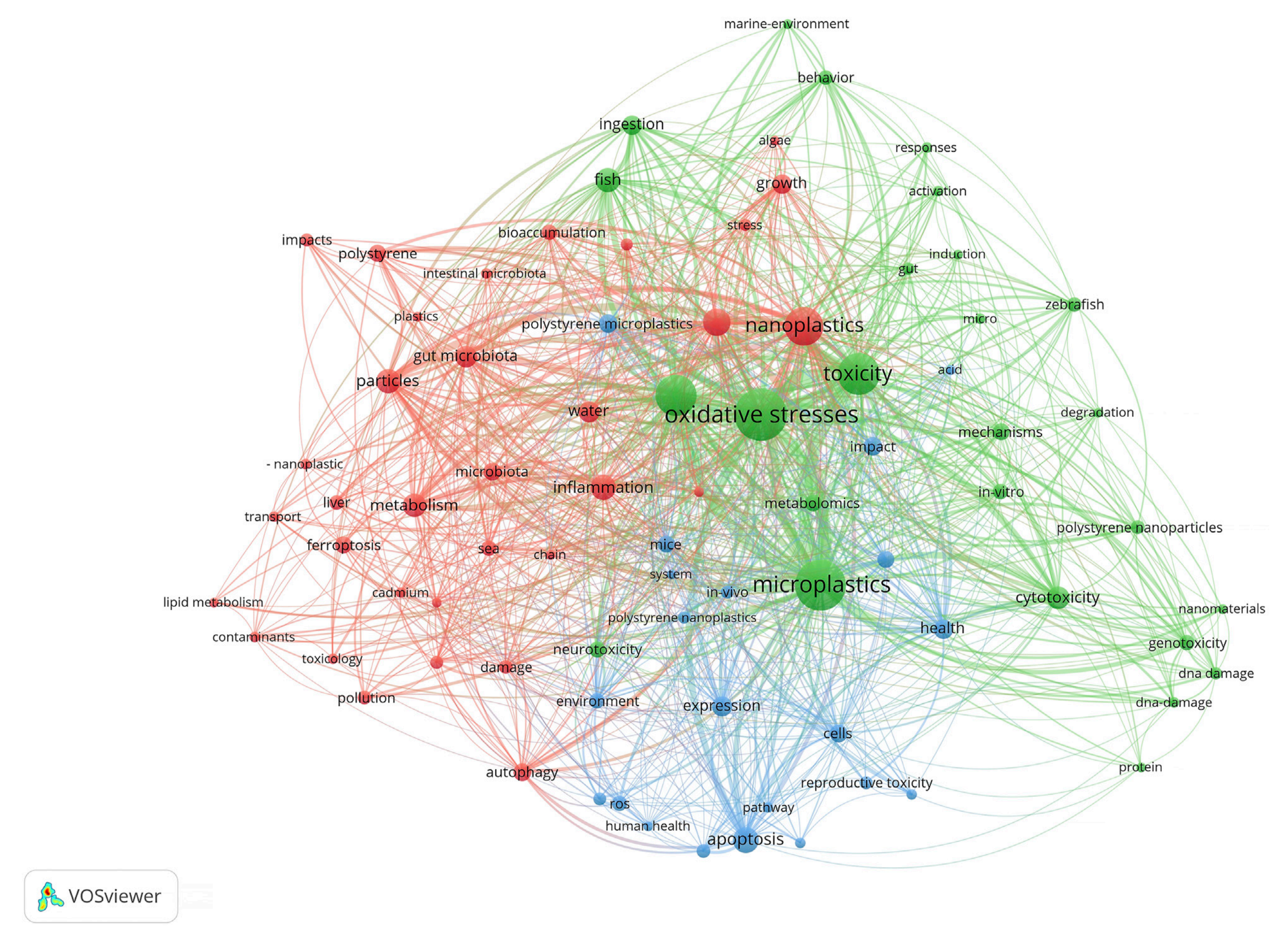

FIGURE 4
Keyword co-occurrence network highlighting oxidative stress-related research in gut health and toxicity mechanisms.

the way for comprehensive intervention strategies to mitigate its impacts. Although microplastics' role in neurotoxicity and reproductive health has been recognized, there is still a lack of long-term exposure assessments and standardized experimental models. Future research should aim to refine exposure quantification methods and develop human-relevant *in vitro* systems to better elucidate microplastics' systemic effects.

This thematic evolution highlights the need for an integrated research approach that not only maps emerging trends but also strengthens interdisciplinary collaboration between toxicology, epidemiology, and regulatory science. Such integration will enable more precise identification of risk factors and inform the development of targeted intervention strategies.

3.4 Keyword co-occurrence

To identify research hotspots and relational networks in microplastic-induced oxidative stress, a keyword co-occurrence analysis was conducted using VOSviewer software, focusing on Topic 2 (Gut Microbiota and Health Risks), Topic 3 (Molecular Mechanisms), and Topic 5 (Health Risk Assessment). This analysis highlighted keywords associated with gut microbiota imbalance, mitochondrial dysfunction, inflammatory pathways, and antioxidant defense systems, offering valuable insights for antioxidant intervention strategies, including zinc and N-acetylcysteine.

3.4.1 Oxidative stress in gut health and toxicity mechanisms

Figure 4 illustrates the keyword co-occurrence network for Topic 2, with terms such as "Microplastics," "oxidative stress," "toxicity," and "inflammation" emerging as core nodes. These nodes reflect their centrality and interconnectedness within the research field. Notably, "oxidative stress" demonstrated strong associations with keywords such as "inflammation," "metabolism," and "gut microbiota," emphasizing its critical role in gut microbiota imbalance and metabolic disorders, aligning with Topic 2's focus on gut health.

The keyword co-occurrence network reveals three distinct clusters that highlight the diverse research focus areas in microplastics-induced oxidative stress. The red cluster centers on "gut microbiota" and "metabolism," emphasizing the impacts of microplastics on gut microbiota imbalance and the associated metabolic disorders. The green cluster focuses on "oxidative stress" and "toxicity," underscoring oxidative stress as a

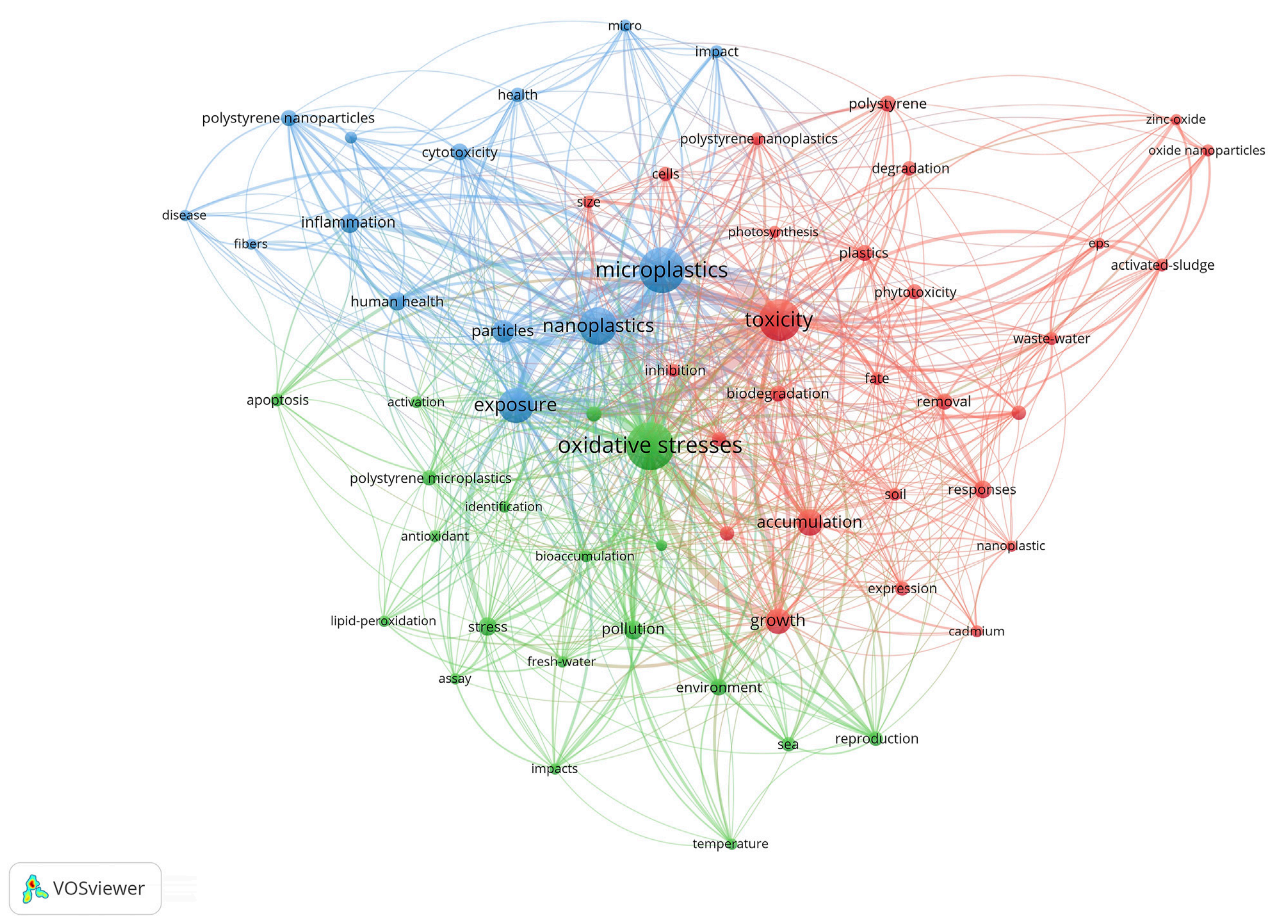

FIGURE 5
Keyword co-occurrence network focusing on molecular mechanisms underlying microplastics-induced oxidative stress.

fundamental mechanism driving microplastics toxicity, particularly through pathways involving inflammation and mitochondrial damage. The blue cluster concentrates on "apoptosis" and "cytotoxicity," shedding light on molecular mechanisms such as cell apoptosis and gene damage induced by microplastics exposure. Together, these clusters underscore the multifaceted nature of oxidative stress in mediating the toxic effects of microplastics across different biological systems.

The findings in Figure 4 underscore the pivotal role of oxidative stress in shaping metabolic health, gut microbiota balance, and toxicity mechanisms. Building on these results, future research will aim to further elucidate the regulatory role of oxidative stress in metabolic disorders and gut microbiota imbalance. Additionally, continued exploration of antioxidant intervention strategies, such as the application of zinc and N-acetylcysteine, holds promise for mitigating the toxic effects of microplastics exposure.

3.4.2 Molecular mechanisms of microplastics-induced oxidative stress

Figure 5 illustrates the keyword co-occurrence network for Topic 3, shedding light on the research hotspots in molecular mechanisms related to Microplastics-induced oxidative stress. Centered around "oxidative stresses," the network comprises multiple clusters, reflecting diverse research directions in cellular damage, oxidative stress defence, and toxicity mechanisms.

Keyword Analysis: "Oxidative stresses" emerges as the central node, exhibiting strong associations with keywords such as "toxicity," "inflammation," "cytotoxicity," and "apoptosis," underscoring its role as a pivotal mechanism in microplastic-induced cellular toxicity. "Microplastics" and "Microplastics" are closely linked to terms like "exposure," "bioaccumulation," and "pollution," highlighting the impact of environmental exposure and biological accumulation on cellular damage. Additionally, "antioxidant" frequently co-occurs with "lipid peroxidation" and "stress," emphasizing the potential of antioxidants in mitigating oxidative stress and its related effects.

The keyword co-occurrence network reveals three distinct clusters that represent key research directions in molecular mechanisms related to microplastics-induced oxidative stress. The green cluster focuses on oxidative stress and bioaccumulation-induced toxicity, emphasizing the harmful effects of microplastics exposure on biological systems. The red cluster examines the migration and accumulation of microplastics and their subsequent impact on gene expression and cell proliferation, highlighting critical pathways of cellular disruption. The blue cluster delves into molecular mechanisms such as inflammation, apoptosis, and gene damage, providing insights into the cellular and

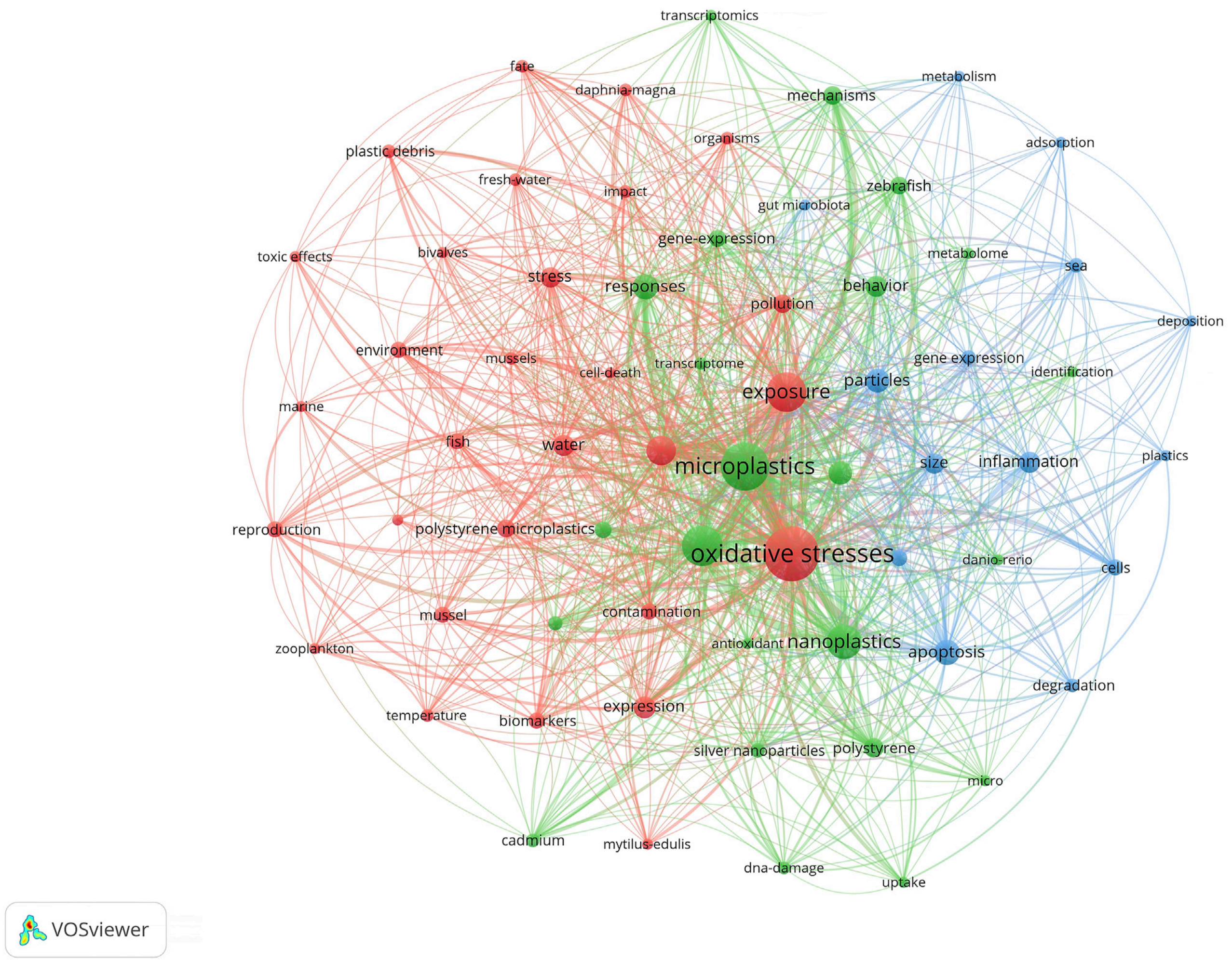

FIGURE 6
Keyword co-occurrence network illustrating research trends related to health risks and antioxidant intervention strategies.

genetic consequences of microplastics toxicity. Together, these clusters underscore the multifaceted nature of microplastics-induced oxidative stress and its systemic impacts.

Figure 5 reflects a paradigm shift in Microplastics research from traditional toxicity assessments to an in-depth exploration of molecular mechanisms. This evolution provides a robust foundation for future studies on the regulatory role of antioxidants in managing oxidative stress. To advance the field, future research should further analyze interconnections between keywords, refining the understanding of antioxidant mechanisms and offering a scientific basis for mitigating health risks associated with microplastics exposure.

3.4.3 Health risks and antioxidant strategies

Figure 6 illustrates the keyword co-occurrence network for Topic 5, highlighting key research hotspots and interconnections in the study of health risks associated with microplastic-induced oxidative stress. The network centers on “oxidative stresses,” “microplastics,” and “Microplasticss,” with clusters focusing on toxicity mechanisms, health risk assessment, and antioxidant defenses. This reflects the extensive and multifaceted nature of research in this field.

Core Keywords and Associations: “Oxidative stresses” emerges as the central node, showing strong associations with keywords such as “inflammation,” “apoptosis,” and “biomarkers,” underscoring its pivotal role in health risk assessment and cellular toxicity. “Microplastics” and “Microplasticss” are closely connected to “exposure” and “pollution,” emphasizing the significant health risks arising from environmental exposure and bioaccumulation. The frequent co-occurrence of “antioxidant” highlights the growing importance of antioxidant research in mitigating oxidative stress and its related health risks, providing a robust theoretical foundation for intervention strategies.

The keyword co-occurrence network reveals three primary clusters that reflect distinct research directions in the study of health risks associated with microplastic-induced oxidative stress. The red cluster focuses on “oxidative stresses” and “toxicity,” addressing microplastic-induced inflammation, apoptosis, and oxidative stress-related biomarkers as critical indicators of cellular damage. The green cluster centers on “pollution” and “bioaccumulation,” highlighting the impact of microplastics on gut microbiota imbalance and metabolic disorders through pathways of bioaccumulation. The blue cluster concentrates on "apoptosis" and "inflammation," delving into Microplastics-induced cellular damage and alterations in gene expression, offering insights into the molecular mechanisms underlying these processes. Together, these clusters illustrate the multifaceted nature of oxidative stress and its systemic implications for health.

Figure 6 underscores the critical role of oxidative stress as an indicator for assessing health risks linked to microplastics exposure. The increasing focus on antioxidant interventions reflects their potential to mitigate these risks by targeting oxidative stress pathways. Future research should delve deeper into the molecular mechanisms underlying oxidative stress and evaluate the multisystem protective effects of antioxidants, offering essential guidance for optimizing health intervention strategies and reducing the adverse impacts of microplastics exposure.

3.5 Linear regression analysis

Table 2 presents the trends in the popularity of eight research themes in Microplastics-induced oxidative stress from 2010 to 2024, as determined by linear regression analysis. Regression coefficients (r values) and significance levels (P values) were employed to evaluate the growth dynamics of each theme, distinguishing between hot and cold topics in the field.

3.5.1 Hot topics

Topic 2 (Gut Microbiota and Health Risks) emerged as the most prominent research hotspot, achieving the highest regression coefficient during 2021–2024 ($r = 20.2$, $P < 0.05$). This trend underscores a growing academic focus on gut microbiota imbalance and metabolic disorders caused by microplastics exposure, particularly its oxidative stress-mediated mechanisms. Topic 3 (Molecular Mechanisms and Cellular Toxicity) has shown consistent growth since 2016, with a regression coefficient of 16.8 during 2021–2024 ($P < 0.05$). This reflects an expanding interest in understanding oxidative stress-induced cellular damage and the role of antioxidant defenses in mitigating microplastics toxicity. Topic 5 (Health Risk Assessment) experienced a significant surge in research activity during 2021–2024 ($r = 12.4$, $P < 0.05$), highlighting its emergence as a key area of study. Research in this theme focuses on the direct impacts of microplastic-induced oxidative stress on immune function, inflammatory responses, and metabolic disorders, providing a robust foundation for assessing the health risks associated with microplastics and their intervention potential.

3.5.2 Cold topics

Topic 7 (Neurotoxicity and Reproductive Health) has seen a decline in research activity since 2019, with a regression coefficient of 8.1 during 2021–2024 ($P > 0.05$), indicating reduced academic focus. Other themes, such as Topic 6 (Antioxidant Mechanism Research) and Topic 8 (Behavioral Impacts), demonstrated moderate research activity but lacked substantial growth, with regression coefficients below 10 and inconsistent significance levels across time periods.

TABLE 2 Hot and cold topics in Microplastics-induced oxidative stress research (2010–2024).

Theme	2010–2012		2013–2015		2016–2018		2019–2021		2021–2024		Total		*p*
	r	+/−	r	+/−	r	+/−	r	+/−	r	+/−	r	+/−	
1	0.0	−	0.5	−	2.5	−	17.0	−	4.0	−	5.4	−	1.21
2	0.0	−	0.0	−	1.0	+	16.5	+	20.2	+	5.7	+	0.00
3	3.8	+	0.0	−	1.5	+	11.0	+	16.8	+	4.9	+	0.00
4	0.0	−	−0.5	−	1.5	+	7.5	+	15.7	+	4.4	+	0.00
5	0.0	−	0.0	−	0.5	+	7.5	+	12.4	+	3.9	+	0.00
6	0.0	−	0.0	−	1.0	+	5.5	+	17.8	+	3.7	+	0.00
7	0.0	−	0.0	−	2.5	−	11.5	−	8.1	−	3.3	−	3.90
8	0.0	−	0.0	−	3.0	+	6.0	+	15.0	+	3.5	+	0.00

Regression Coefficient (r): Hot/Cold Topic: +/−

However, it is important to note that the observed decline in publication volume for some cold topics may not necessarily indicate a decrease in their scientific relevance. Instead, these topics might be experiencing a temporary plateau due to shifts in research focus, methodological advancements, or funding priorities. For instance, while neurotoxicity and reproductive health effects of microplastics have received less attention in recent years, future studies incorporating novel analytical techniques or interdisciplinary approaches may reinvigorate interest in these areas. Similarly, antioxidant mechanism research, despite its slower growth, remains a critical component of microplastics toxicity mitigation and could see renewed focus as new antioxidant strategies emerge. Therefore, rather than interpreting these topics as diminishing in importance, they should be considered as potential areas for future exploration and development.

3.5.3 Evolution of research activity

From 2010 to 2018, research activity in Microplastics-induced oxidative stress was minimal, with regression coefficients near zero, reflecting the nascent stage of the field. However, since 2019, research activity has surged, driven primarily by advancements in Topic 2, Topic 3, and Topic 5. By 2021–2024, the research focus has diversified, moving beyond foundational studies on gut microbiota and metabolic disorders to encompass cellular toxicity mechanisms and broader environmental health impacts.

3.5.4 Future directions

Table 2 indicates that research in Microplastics-induced oxidative stress is progressing toward an interdisciplinary and mechanism-diversified approach. Future studies should prioritize hot topics such as Topic 2 and Topic 3 to deepen understanding of the oxidative stress pathways contributing to health risks. Additionally, the rapid growth of Topic 5 underscores the importance of developing antioxidant interventions to mitigate metabolic disorders and inflammatory biomarker expression, offering substantial potential for health risk mitigation strategies in the context of microplastics exposure.

4 Discussion

This study highlights the evolutionary trajectory of the study of microplastics-induced oxidative stress, revealing its early developmental stage (2010–2018), low publication volume, and slow growth. During this period, microplastics pollution did not receive enough academic attention. However, there has been a surge in research activity since 2019 and an exponential increase after 2020, reflecting the global awareness of microplastics pollution and its associated health risks. Oxidative stress has become a central toxicological mechanism of the health effects of microplastics, driving this increased research interest.

Research trends indicate a shift in focus over time. Initial studies were primarily concerned with the environmental distribution and ecological impacts of microplastics (Cai et al., 2021; Sharma et al., 2021; Yang et al., 2021; Medyńska-Juraszek and Jadhav, 2022; Weber et al., 2023), whereas more recent investigations have expanded to address the potential threats to human health (Vethaak and Legler, 2021; Peng et al., 2022; Saadati et al., 2022; Sincihu et al., 2023; Zając et al., 2024). This transition underscores the growing awareness of the broader implications of microplastics exposure, prompting the academic community and policymakers to seek actionable insights.

Thematic analysis through LDA modeling identified eight primary themes, encompassing ecological toxicity, health risks, and molecular mechanisms. Topic 1 (Ecological Impacts) highlights the oxidative stress-mediated effects of microplastics on aquatic ecosystems, such as fish, underscoring the ecological dimensions of microplastics pollution. However, its link to dietary antioxidant interventions remains underexplored (Cuffaro et al., 2023; Wu Y. et al., 2023). Topic 2 (Health Risk Assessment) has rapidly gained prominence, emphasizing oxidative stress-induced gut microbiota imbalance and metabolic disorders. This offers a theoretical basis for interventions using dietary antioxidants like zinc and lipoic acid (Paramanik, 2018). Topic 3 (Molecular Mechanisms) delves into oxidative stress-induced apoptosis, gene damage, and inflammatory pathways, providing direction for targeted antioxidant strategies, including mitochondrial protection and anti-inflammatory measures (Rives et al., 2020). Emerging themes (Topic 7 and Topic 8) explore the impacts of microplastics on neurotoxicity, reproductive health, and behavioral changes, highlighting the need for further research into neural health protection and behavioral outcomes.

Overall, the research focus is transitioning from traditional ecological toxicity assessment to health risk assessment and molecular mechanism exploration. Oxidative stress is increasingly recognized as a central pathway (Facciolà et al., 2021; Chen et al., 2022; Haldar et al., 2023), providing opportunities for dietary interventions. Future studies should emphasize the application of antioxidants in multisystem protection and investigate their specific mechanisms for mitigating microplastic-induced health risks (Wu H. et al., 2023).

Through keyword co-occurrence analysis, this study unveils the core research directions and their associated networks in the field of microplastic-induced oxidative stress. The keyword network, centered around "oxidative stress," "nanoplastics," and "microplastics," highlights the predominant role of oxidative stress as the central mechanism of microplastics toxicity. These keywords significantly co-occur with terms such as "inflammation," "apoptosis," "gut microbiota," and "metabolism," indicating the pivotal role of oxidative stress in inflammation, cellular apoptosis, metabolic disorders, and dysbiosis of the gut microbiota.

The results of the keyword co-occurrence analysis further emphasize oxidative stress as the central mechanism of microplastics toxicity. Keywords such as "inflammation," "apoptosis," "gut microbiota," and "metabolism" prominently co-occur with "oxidative stress," reflecting its pivotal role in driving systemic effects like inflammation, metabolic disorders, and gut microbiota dysbiosis. Cluster analysis revealed interconnected research directions: the red cluster focuses on inflammation and oxidative biomarkers, the green cluster on metabolic disorders and gut microbiota imbalance, and the blue cluster on cellular damage and apoptosis. This interconnected structure underscores the complexity of microplastics-induced oxidative stress and provides a roadmap for future investigations.

Future research should delve into oxidative stress-related molecular pathways, particularly the roles of dietary antioxidants in regulating inflammation and metabolic disorders (Idres et al., 2021; Wu H. et al., 2023). Additionally, research should expand to examine cross-system effects, such as the combined impacts of microplastics exposure on neural, gut, and metabolic systems, providing a comprehensive foundation for antioxidant-based intervention strategies.

The findings of this study have significant implications for plastic waste management policies and public health interventions. Given that oxidative stress has been identified as a central mechanism of microplastics toxicity, this insight can inform environmental regulations aimed at stricter control of plastic waste, reduction of single-use plastics, and enhancement of microplastics pollution monitoring. Furthermore, our findings suggest that antioxidant interventions hold promise in mitigating microplastic-induced oxidative stress, offering a potential avenue for public health strategies. Future policy efforts could consider integrating antioxidant-rich dietary recommendations into public health guidelines to mitigate the adverse effects of microplastics exposure. For instance, dietary supplementation with antioxidants such as zinc and N-acetylcysteine may help strengthen oxidative defense mechanisms and reduce health risks associated with microplastics exposure. As a result, an interdisciplinary approach is necessary—not only to advance the toxicological understanding of microplastics but also to shape regulatory measures that minimize environmental exposure and optimize public health interventions.

Despite significant progress, notable research gaps remain. The role of dietary antioxidants, such as zinc and N-acetylcysteine, in mitigating oxidative stress is underexplored. Furthermore, existing studies predominantly address single-system effects (e.g., gut or liver) (Grodzicki et al., 2021; Matthews et al., 2021; Haldar et al., 2023), with limited focus on cross-system interactions and the chronic health risks of prolonged microplastics exposure (Smith et al., 2018; Zhang et al., 2020). Investigating the combined impacts of microplastics exposure on neural, metabolic, and immune systems is essential to comprehensively understand its systemic effects.

This study provides a systematic bibliometric analysis and thematic exploration, revealing the core trends and research hotspots in microplastics-induced oxidative stress. The findings reaffirm the centrality of oxidative stress in microplastics toxicity mechanisms and highlight the promising potential of health risk assessments and antioxidant interventions. These insights not only advance the understanding of microplastic-induced health risks but also offer a scientific foundation for designing multi-systemic, collaborative intervention strategies to mitigate their impacts.

While the emergence of health risk assessment as a dominant theme aligns with increasing public and regulatory concerns, the prioritization of certain research topics may also reflect funding biases. Western countries, particularly those with strong environmental policies, are leading contributions to this field, potentially underrepresenting findings from developing regions. These factors should be considered when interpreting publication trends.

5 Conclusion

Through bibliometric analysis and LDA topic modeling, this study provides a comprehensive exploration of the research dynamics on microplastics-induced oxidative stress from 2010 to 2024. The findings reveal a significant surge in publication volume since 2019, reflecting growing global attention to the health and environmental risks posed by microplastics. Research hotspots have shifted over time, transitioning from ecological toxicity studies to a more nuanced focus on health risk assessment and molecular mechanism exploration. "Oxidative stress" has emerged as a central theme, closely associated with key concepts such as "inflammation," "apoptosis," and "gut microbiota," highlighting its pivotal role in the toxicological effects of microplastics.

This study underscores the critical importance of health risk assessment (e.g., Topic 2 and Topic 5) in understanding the broader implications of microplastic exposure. It also highlights the promising potential of antioxidant interventions, such as dietary strategies, to mitigate oxidative stress-induced health risks. Recent studies have begun to explore the cross-system effects of microplastics exposure, particularly the interplay between the gastrointestinal, liver, neural, and immune systems. These studies suggest that oxidative stress not only disrupts gut microbiota homeostasis but also contributes to neuroinflammation, hepatic dysfunction, and immune dysregulation, leading to systemic health consequences. However, notable research gaps remain, particularly in the areas of cross-system interactions and the long-term impacts of microplastics exposure. Further interdisciplinary research is needed to comprehensively understand the mechanisms underlying these systemic effects and to develop targeted antioxidant strategies for mitigating multisystem toxicity. The role of dietary antioxidants, such as zinc and N-acetylcysteine, in providing multisystem protection warrants further investigation.

The findings of this study offer valuable insights into the complex and systemic effects of microplastics on human health and ecosystems. They provide a robust theoretical foundation for advancing antioxidant-based intervention strategies and encourage the development of multi-disciplinary approaches to address the health risks associated with microplastics exposure. By identifying current research gaps and emerging trends, this study lays the groundwork for future research directions, fostering a deeper understanding of the molecular and systemic impacts of microplastics and guiding efforts to mitigate their adverse effects. Furthermore, this bibliometric analysis serves as a strategic roadmap for guiding targeted interventions and policy initiatives aimed at mitigating microplastics' health risks, reinforcing the significance of evidence-based decision-making in environmental health regulation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YY: Data curation, Formal Analysis, Software, Writing – original draft. YC: Software, Supervision, Validation, Visualization, Writing – review and editing. YG: Formal Analysis,

Methodology, Writing – original draft. YJ: Formal Analysis, Methodology, Writing – original draft. FX: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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