Microplastic toxicity in marine microalgae: an ecotoxicological synthesis of experimental biological responses

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Abstract

As a pervasive form of marine pollution, microplastics (MPs) are widely distributed across coastal and oceanic systems, raising concerns about their ecological impacts.This review provides an evidence-based synthesis of microplastic–microalgae interactions, integrating physiological responses and associated toxicity pathways.Marine microalgae are particularly relevant in this context because they constitute the foundation of marine food webs and play a central role in primary productivity and global biogeochemical cycling. This study synthesizes experimental ecotoxicological evidence on the effects of microplastics on marine microalgae, with the aim of identifying dominant toxicity endpoints and key knowledge gaps relevant to ecotoxicological evaluation. Publications indexed in Web of Science and Scopus from 1970 to August 2025 were systematically screened, resulting in 54 eligible studies. The analysis revealed a rapid expansion of research on microplastic–microalgae interactions, with most studies focusing on polystyrene, polyethylene, and polyvinyl chloride particles within the size range of 0.5–5000 µm. The most frequently reported biological responses included growth inhibition, oxidative stress, alterations in photosynthetic performance, and changes in cellular morphology. Despite this progress, several ecologically relevant endpoints remain insufficiently investigated, including aggregate formation, particle sinking dynamics, DNA damage, and long-term exposure under environmentally realistic conditions. Furthermore, most studies rely on short-term laboratory assays using simplified exposure scenarios, which may limit the

ecological relevance of current knowledge. Taken together, the available evidence highlights key research priorities and outlines directions for improving experimental ecotoxicological studies.

Keywords: Ecotoxicology; Marine microalgae; Microplastics; Oxidative stress; Photosynthesis; Biological responses

1. Introduction

Microplastics (MPs) have emerged as pervasive environmental contaminants due to their widespread occurrence across aquatic, terrestrial, and atmospheric compartments (Nava and Leoni 2021). Over recent decades, exponential growth in plastic production and consumption has intensified the release of plastic debris into the environment; global plastic production has increased by approximately 200% over the last three decades (OECD 2022). This plastic debris undergoes continuous fragmentation and persists for extended periods, resisting physical, chemical, and biological degradation (Cole et al. 2011). Consequently, MPs have become globally distributed pollutants, raising significant concerns regarding their ecological implications (Wang et al. 2025b).In marine environments, microplastics are now recognized as a major component of anthropogenic pollution, affecting ecosystem structure and function across multiple spatial scales.

Plastic debris is typically classified by size into macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (1 µm–5 mm), and nanoplastics (1–1,000 nm) (Andrady 2017). Based on their origin, MPs are categorized as either primary—intentionally manufactured at microscopic scales for industrial or cosmetic applications—or secondary, resulting from the degradation of larger items (Hernandez et al. 2017). Secondary MPs are generated through a combination of physical processes (e.g., mechanical abrasion, ultraviolet radiation, and temperature fluctuations), chemical pathways (e.g., oxidation and hydrolysis), and biological interactions, such as colonization by microorganisms that form biofilms on plastic surfaces (Andrady 2011).

MPs exhibit diverse morphologies, including fibers, fragments, pellets or beads, films, and foams, reflecting distinct sources and degradation pathways (Andrady 2011). These particles are composed of various polymers, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polycarbonate (PC), polyethylene terephthalate (PET), nylon, and cellulose acetate (Cole et al. 2011). Their physicochemical properties—including size, shape, polymer composition, and surface characteristics—largely determine their environmental behavior, bioavailability, and interactions (Wright et al. 2013).

The occurrence of MPs has been documented in virtually all aquatic environments, including rivers, lakes, estuaries, coastal zones, and open oceans, with concentrations fluctuating according to geographic location, hydrodynamics, and anthropogenic pressure (Horton et al. 2017). In marine systems, MPs are recognized not only as physical stressors but also as dynamic vectors capable of adsorbing and transporting metals, persistent organic pollutants (POPs), pharmaceuticals, and other emerging contaminants (Rochman et al. 2013). This multifunctional role reinforces their classification as complex environmental stressors that can alter the fate and transport of contaminants across environmental compartments (Koelmans et al. 2016).

As the abundance of MPs increases, so does their bioavailability to marine organisms across multiple trophic levels (Wright et al. 2013). Numerous studies have documented MP ingestion and associated adverse effects in zooplankton, benthic invertebrates, mollusks, crustaceans, and fish (Cole et al. 2013; Lusher et al. 2013). These interactions raise critical questions regarding trophic transfer, biomagnification, and ecosystem-level impacts, particularly when MPs act synergistically with co-occurring chemical contaminants (Rochman et al. 2013).

Marine microalgae occupy a central position in aquatic ecosystems as primary producers, supporting aquatic food webs, driving biogeochemical cycles, and contributing significantly to global carbon sequestration (Falkowski et al.

1998). Due to their small size, high surface-area-to-volume ratio, and continuous exposure to surrounding water, microalgae are particularly vulnerable to MPs exposure (Bhattacharya et al. 2010). Experimental studies have demonstrated that MPs may impair microalgal growth, photosynthetic activity, cellular morphology, and may induce oxidative stress and alter biochemical composition(Lagarde et al. 2016; Zhang et al. 2017). These effects may arise from physical cell-surface interactions, shading effects that limit light availability, or chemical interactions involving plastic additives and adsorbed pollutants (Bhattacharya et al. 2010; Rist et al. 2017).

Such alterations in microalgal physiology have implications extending beyond organism-level toxicity. Changes in primary productivity, photosynthetic efficiency, and biomass production may propagate across food webs, influencing nutrient cycling and essential ecosystem services (Falkowski et al. 1998; Rist et al. 2018). Consequently, understanding MPs–microalgae interactions is critical for evaluating the broader environmental risks associated with plastic pollution (SAPEA 2019).

However, the diversity of experimental approaches has made it difficult to obtain an integrated understanding of microplastic effects on marine microalgae. Despite the rapid expansion of research in this field, the scientific literature addressing microplastic–marine microalgae interactions remains fragmented and heterogeneous, characterized by wide variations in experimental designs, particle characteristics, exposure concentrations, and evaluated endpoints (Hartmann et al. 2019). Evidence synthesis provides an important framework for integrating experimental ecotoxicological studies, identifying dominant toxicity endpoints, and highlighting critical knowledge gaps related to microplastic exposure in marine microalgae (Donthu et al. 2021).

To address these challenges, publications indexed in Web of Science and Scopus from 1970 to August 2025 (Falagas et al., 2008; Mongeon and Paul-Hus, 2016), this study synthesizes experimental evidence on the most frequently investigated polymer types, particle sizes, exposure conditions, and biological endpoints reported for marine microalgae. In addition, the temporal development of this research field and its main geographic and scientific contributors are described to provide a structured overview of the current state of knowledge.Because marine microalgae constitute the foundation of aquatic food webs and play a key role in global primary production (Falkowski et al., 1998), understanding their responses to microplastic exposure is essential for improving ecotoxicological interpretation and experimental standardization and guiding future experimental research.Unlike previous reviews that broadly address microplastic impacts on aquatic organisms, this study provides a focused synthesis of experimental evidence on marine microalgae, emphasizing the integration of experimental evidence with environmental relevance to support ecotoxicological interpretation and experimental standardization.

2. Materials and Methods

2.1 Data sources and search strategy

A systematic literature search was conducted using two major scientific databases, Web of Science and Scopus. These platforms were selected due to their comprehensive coverage of peer-reviewed environmental and toxicological literatureand their frequent use in systematic evidence syntheses (Falagas et al. 2008; Mongeon and Paul-Hus 2016). The combined use of these databases minimizes indexing bias and ensures a more robust evidence base for synthesis (Vieira and Gomes 2009; Donthu et al. 2021).

The search was first performed in February 2024 and updated in August 2025 to include the latest publications in this rapidly evolving field. All retrieved records were exported in BibTeX format for standardized processing (Aria and Cuccurullo 2017). The search strategy employed combinations of keywords related to "microplastics," "marine microalgae," and "toxicity," refined using Boolean operators within titles, abstracts, and author keywords (Zupic and Čater 2015).

2.2 Inclusion and exclusion criteria

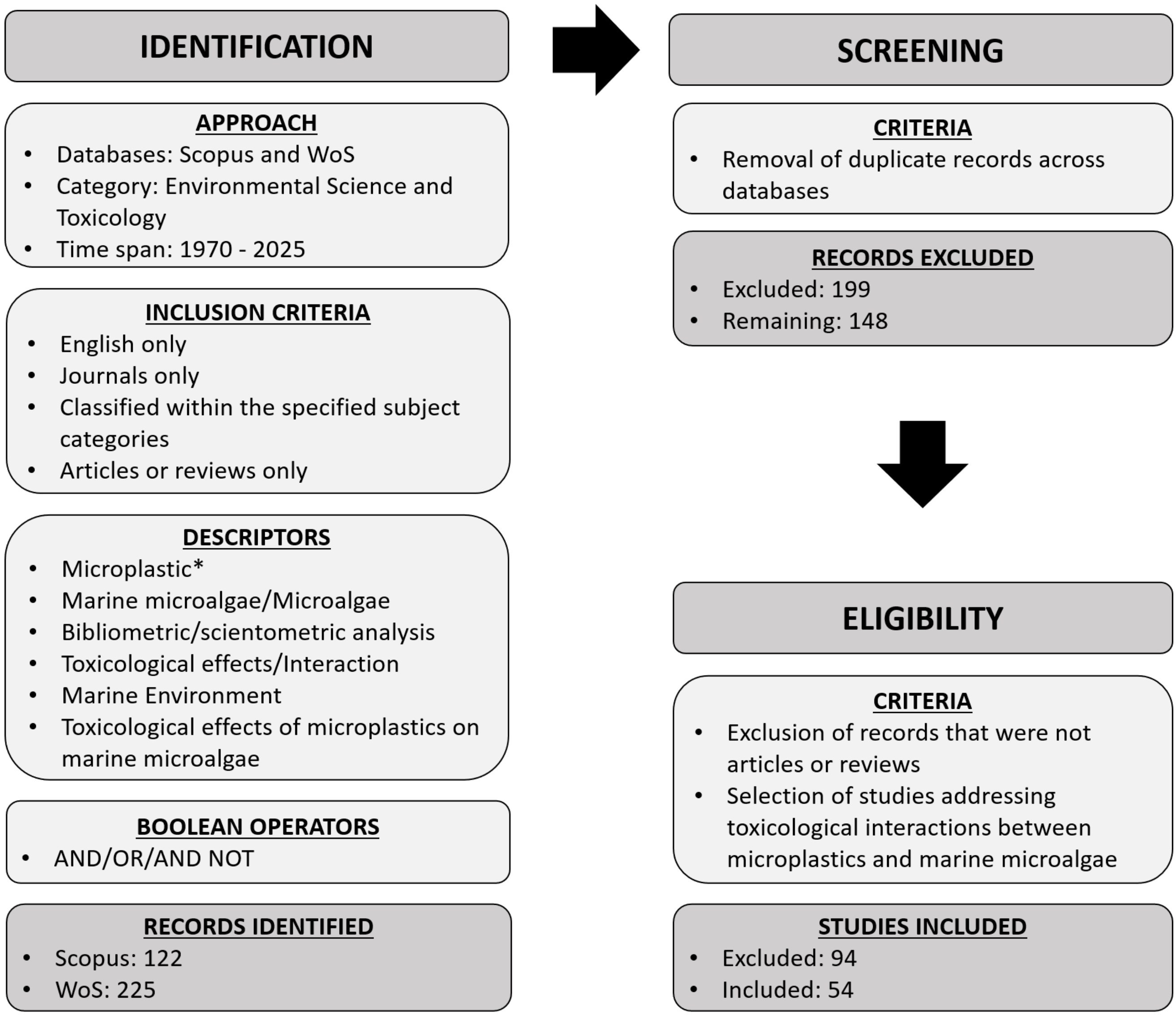
To ensure relevance and quality, the following inclusion criteria were defined according to established guidelines for systematic literature reviews (Donthu et al. 2021): (i) publications indexed in peer-reviewed journals within the “Environmental Science” and “Toxicology” categories; (ii) a timeframe spanning 1970 to August 2025, corresponding to the period of accelerated plastic production and growing environmental concern regarding plastic pollution (OECD 2022); (iii) articles published in English; and (iv) original research articles and review papers.

Conversely, book chapters, conference proceedings, abstracts, data papers, editorials, or gray literature were excluded to maintain citation-based consistency (Falagas et al. 2008). Studies focusing exclusively on freshwater systems, sediments, or non-microalgal taxa were also excluded to preserve thematic focus.In addition, only studies reporting experimental exposure to microplastics and evaluating biological responses in marine microalgae were considered.

2.3 Screening procedure and data selection

The selection followed a multi-stage screening process consistent with systematic literature review frameworks (Zupic and Čater 2015; Donthu et al. 2021). After compiling records from both databases, duplicates were removed using Digital Object Identifiers (DOIs), author names, and publication titles. Titles, abstracts, and keywords were then individually screened for relevance. Articles that did not specifically address interactions between MPs and marine microalgae were excluded. The final dataset comprised 54 publications. The screening procedure followed a sequential selection approach based on title, abstract, and full-text evaluation to ensure that only studies directly addressing experimental interactions between MPs and marine microalgae were included. The selection workflow is summarized in Fig. 1.

Figure 1. Workflow of the literature search, screening, and selection process for studies addressing microplastic–microalgae interactions.



2.4 Quantitative literature analysis and evidence mapping

Quantitative evidence mapping was conducted using the bibliometrix package (R statistical software) to support the interpretation of patterns within experimental ecotoxicological studies (Aria and Cuccurullo 2017). The biblioshiny web interface was utilized to visualize data distributions and generate graphical outputs, facilitating the synthesis of information related to experimental approaches, study characteristics, and evaluated biological endpoints.Journal-level information and publication patterns were used only to contextualize the experimental ecotoxicological evidence. These analyses were applied exclusively as a complementary tool to support the interpretation of experimental ecotoxicological evidence, rather than as a primary objective of the study.

This approach was complemented by integrating qualitative and quantitative data extracted from the selected publications, enabling a deeper interpretation of variability in experimental design and thematic evolution (Zupic and Čater 2015). For each article, a systematic data extraction was performed, covering the year of publication, geographic origin, taxonomic classification of microalgae, polymer type and particle size, experimental setting, analytical methods, and evaluated biological endpoints.

2.5 Classification of endpoints and data synthesis

The endpoint classification was designed to align the literature synthesis with commonly used ecotoxicological response categories applied in laboratory toxicity tests with phytoplankton and primary producers. To facilitate comparative analysis, reported endpoints were grouped into functional categories based on similarities in biological focus, following established frameworks in environmental toxicology (Wright et al. 2013; Hartmann et al. 2019). This classification enabled the identification of dominant research themes, frequently assessed endpoints, and underexplored areas within the literature.The synthesized findings provided the framework for the subsequent Results and Discussion sections, emphasizing research trends, methodological heterogeneity, and existing knowledge gaps concerning the impacts of MPs pollution on marine microalgae.

3. Results and Discussion

3.1 Selected publications

The initial systematic search conducted in the Scopus and Web of Science (WoS) databases retrieved a total of 347 publications, including 122 records from Scopus and 225 from WoS (Fig. 1). After removing duplicate records based on Digital Object Identifiers (DOIs), titles, and author names, 148 publications remained for further screening.During the subsequent screening stages, titles, abstracts, and keywords were evaluated to determine their relevance to the research scope. Studies that did not specifically address interactions between MPs and marine microalgae were excluded. Following this process, 94 articles were removed due to lack of thematic relevance or because they focused on freshwater systems, sediments, or non-microalgal taxa.After the full screening procedure, a final dataset of 54 publications addressing experimental interactions between MPs and marine microalgae was obtained (Fig. 1). The complete list of selected studies used in the literature synthesis and evidence mapping is provided in Supplementary Table S1.

3.2 Temporal trends and characteristics of selected studies

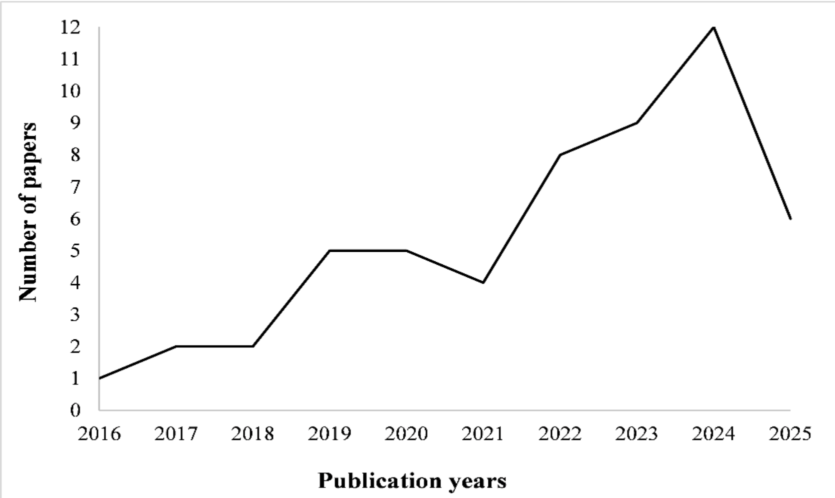
Among the selected publications, 47 were original research articles (87.0%) and 7 were review articles (13%) (Table 1). Although the search parameters covered the period from 1970 to 2025, all eligible studies were published between 2016 and August 2025, indicating that research on microplastic–microalgae interactions is a relatively recent field. The selected studies were distributed across 14 scientific journals and involved a total of 274 authors, reflecting the growing engagement of the scientific community in investigating the ecological effects of MPs on marine primary producers.

Table 1. General characteristics of the selected publications on microplastic toxicity in marine microalgae.

Parameter	Value
Publication time range	2016 to 2025
Average annual growth rate (%)	47
Number of journals	14
Number of journals in the Environmental Science category	10
Number of journals in the Toxicology category	4
Number of publications analyzed	54
Number of publications of the original article type	47
Number of review-type publications	7
Average age of publications (years)	3.04
Total number of publication references	1813
Total number of authors	274
Publications with international co-authors (%)	9.26

The temporal distribution of studies reveals a marked increase in research activity over the past decade (Fig. 2). The number of publications rose from a single study in 2016 to 12 in 2024, demonstrating a consistent upward trend. This pattern reflects the increasing recognition of MPs as emerging contaminants in marine environments and the growing interest in understanding their ecological impacts on primary producers.

Figure 2. Temporal distribution of scientific publications on microplastic toxicity in marine microalgae between 2016 and August 2025.



The predominance of multi-authored studies, with no single-author publications identified, highlights the collaborative nature of experimental ecotoxicology research. However, only 9.26% of the publications involved international co-authorship, suggesting that research efforts remain largely concentrated within national research groups. This limited international collaboration may contribute to methodological heterogeneity across studies, particularly in relation to experimental design, particle characteristics, and exposure conditions.

Overall, the rapid increase in publication output, combined with the expansion of collaborative research networks, indicates that this field is undergoing accelerated development. In addition, the growing number of studies suggests a shift toward more detailed investigations of physiological and biochemical responses, reinforcing the importance of ecotoxicological approaches for evaluating the environmental risks associated with microplastic contamination.

3.3 Spatial distribution of publications

The analysis identified contributions from 15 countries involved in research on the toxicological effects of MPs on marine microalgae (n = 54). China accounted for the largest share of publications (51.85%), followed by Spain and South Korea (7.40% each), and Portugal (5.55%). France, Italy, Belgium, and Brazil each contributed 3.70% of the publications, while Argentina, the Czech Republic, Egypt, India, Malaysia, the Netherlands, and Poland published one article each during this period.This distribution is consistent with global trends reported for microplastic research, which consistently identified China as a leading contributor to scientific output in aquatic ecotoxicology (Oliveira et al. 2020; Akinpelu et al. 2022; Gao et al. 2022). This dominance may be associated with substantial increases in research funding, notably through the expansion of the National Natural Science Foundation of China since 2015 (Yang 2016), as well as national prioritization of research addressing plastic pollution.

Despite the global nature of the plastic crisis, international collaboration remains relatively limited; only seven of the 54 analyzed articles involved Multiple-Country Participation (MCP) (Table 2). Among these, China spearheaded three publications in partnership with authors from Indonesia, Australia, Malaysia, South Korea, Iran, the Czech Republic, Pakistan, and Argentina. Remaining collaborations included efforts between Spain and France, two by France with Spain and Australia, and one by Egypt with Saudi Arabia. This low MCP rate suggests that research on microplastic–microalgae interactions is still largely conducted within national boundaries, highlighting a significant opportunity for future cross-border initiatives to facilitate methodological standardization in future studies.

Table 2. Spatial distribution of the most productive countries among the selected publications on microplastic toxicity in marine microalgae (n = 54).

Classification	Country	Articles	SCP	MCP
1	China	28	25	3
2	Spain	4	3	1
3	South Korea	4	4	0
4	Portugal	3	3	0
5	France	2	0	2
6	Italy	2	2	0
7	Belgium	2	2	0
8	Brazil	2	2	0
9	Argentina	1	1	0
10	Czech Republic	1	1	0
11	Egypt	1	0	1
12	India	1	1	0
13	Malaysia	1	1	0
14	Netherlands	1	1	0
15	Poland	1	1	0
Total		**54**	**47**	**7**

SCP=number of publications from a single country. MCP=number of publications from multiple countries.Total = number of published articles.

3.4 Distribution of studies across environmental and ecotoxicological journals

The distribution of studies across scientific journals indicates that research on interactions between microplastics and marine microalgae is concentrated within a relatively small group of environmental and ecotoxicological journals (Table 3). Environmental Pollution and Science of the Total Environment account for the highest number of publications, followed by journals focused on aquatic toxicology and environmental contamination. This pattern reflects the growing scientific interest in understanding the ecological consequences of microplastic exposure in aquatic primary producers and highlights the relevance of this topic within the broader fields of environmental pollution and ecotoxicology. The concentration of studies in journals addressing contaminant dynamics, aquatic toxicology, and ecosystem health also illustrates the increasing integration of microplastic research into ecotoxicological evaluation frameworks.Overall, this distribution reinforces the recognition of MPs as emerging contaminants capable of affecting key biological processes in marine primary producers and potentially influencing ecological functioning in aquatic ecosystems.

Table 3. Distribution of selected studies across journals publishing research on microplastic toxicity in marine microalgae (n = 54).

Classification	Journal	Articles
1	*Environmental Pollution*	13
2	*Science of the Total Environment*	10
3	*Marine Environmental Research*	6
4	*Journal of Hazardous Materials*	5
5	*Aquatic Toxicology*	4

6	*Chemosphere*	4
7	*Water Research*	3
8	*Ecotoxicology and Environmental Safety*	2
9	*Marine Pollution Bulletin*	2
10	*Environmental Chemistry Letters*	1
11	*Environmental Research*	1
12	*Environmental Science and Pollution Research*	1
13	*Frontiers in Toxicology*	1
14	*Regional Studies in Marine Science*	1

3.5Key findings from influential studies

The scientific literature has substantially advanced the understanding of interactions between microplastics (MPs) and marine primary producers, suggesting that microplastic exposure may induce a wide range of physiological and biochemical responses in microalgae. Across experimental studies, converging evidence suggests that growth inhibition and impairment of photosynthetic performance are among the most consistent responses, reflecting the sensitivity of primary producers to particle-induced stress.

These toxic effects may arise from multiple, often interconnected mechanisms, including both physical and biochemical pathways. Such responses are often mediated by oxidative stress pathways, where the overproduction of reactive oxygen species (ROS) leads to lipid peroxidation, membrane damage, and impairment of cellular functions.This framework contributes to understanding potential pathways through which microplastic exposure may translate into functional impairments at the cellular level, distinguishing this synthesis from predominantly descriptive approaches.Direct physical interactions between MPs and algal cell surfaces can lead to mechanical interference, as demonstrated in the diatom *Skeletonema costatum* (Zhang et al. 2017). In addition, microplastics can influence particle dynamics in the water column through hetero-aggregation processes, which are highly species-specific and may alter particle buoyancy and vertical transport (Long et al. 2017). Such interactions can modify light availability and nutrient exchange, indirectly affecting microalgal metabolism and growth.

Beyond physical interactions, MPs may also act as vectors for chemical contaminants, thereby modifying the toxicity of co-occurring substances. Prata et al. (2018) demonstrated that the presence of MPs can alter the toxicity of pharmaceutical compounds such as procainamide and doxycycline. These combined effects are influenced by particle size and the relative dimensions of microplastics and algal cells, which determine the extent of surface interactions and cellular uptake (Chae et al. 2019). More recent studies also highlight the role of algal extracellular polymeric substances (EPS) in mediating aggregation processes, potentially affecting both the environmental fate of MPs and their biological availability (Lim et al. 2024; Sioen et al. 2024).

In addition to mechanistic insights, previous reviews (Prata et al. 2019; Nava and Leoni 2021) emphasize that microplastic exposure may disrupt key ecological processes, including population dynamics, nutrient cycling, and energy transfer within marine ecosystems. Reported effects include reductions in chlorophyll content, alterations in photosynthetic activity, and morphological changes, all of which may compromise primary productivity. Importantly, these responses are not uniform across taxa, indicating that species-specific traits play a critical role in modulating microplastic toxicity.

Collectively, the available evidence indicates that microplastic toxicity appears to result from a combination of physical and biochemical interactions. The most influential studies in this field, based on citation metrics, are summarized in Table 4.

Table 4. Ten most cited articles identified among the selected publications (n = 54).

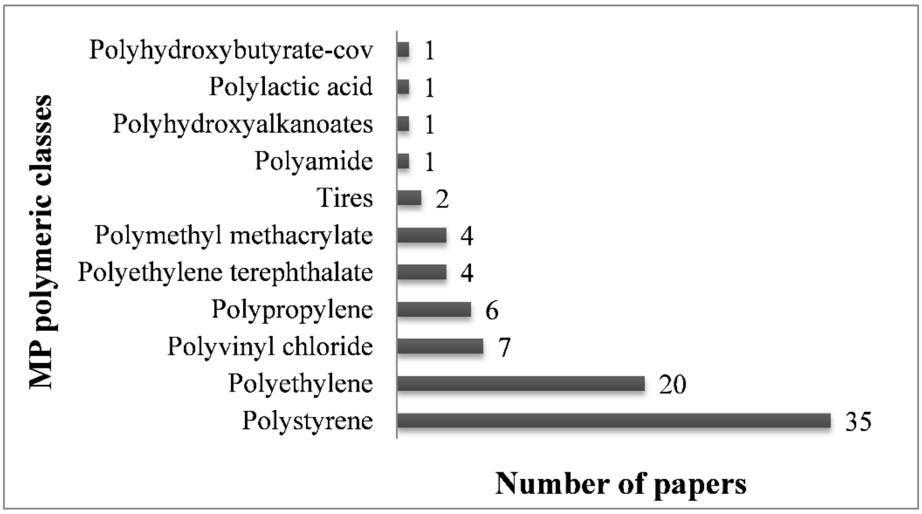
References	Title	Journal	Total Citations	Average Citations per Year
Zhang et al. *(2017)*	Toxic effects of microplastic on marine microalgae *Skeletonema costatum*: Interactions between microplastic and algae	*Environmental Pollution*	476	59.5
*Sjollema*et al. *(2016)*	Do plastic particles affect microalgal photosynthesis and growth?	*Aquatic Toxicology*	410	45.5
Prata et al. *(2019)*	Effects of microplastics on microalgae populations: A critical review	*Science of the Total Environment*	232	38.6
Long et al. *(2017)*	Interactions between polystyrene microplastics and marine phytoplankton lead to species-specific hetero-aggregation	*Environmental Pollution*	225	28.1
Prata et al. *(2018)*	Influence of microplastics on the toxicity of the pharmaceuticals procainamide and doxycycline on the marine microalgae *Tetraselmis chuii*	*Aquatic Toxicology*	215	30.7
Nava and Leoni (2021)	A critical review of interactions between microplastics, microalgae, and aquatic ecosystem function	*Water Research*	161	40.2
Cunha et al. *(2019)*	Marine vs freshwater microalgae exopolymers as biosolutions to microplastics pollution	*Environmental Pollution*	113	18.8
Chae et al. *(2019)*	Effects of micro-sized polyethylene spheres on the marine microalgae *Dunaliella salina*: Focusing on the algal cell to plastic particle size ratio	*Aquatic Toxicology*	102	17.0
Zhao et al. *(2019)*	The interactions between micro polyvinylchloride (mPVC) and marine dinoflagellate *Kareniamikimotoi*: The inhibition of growth, chlorophyll and photosynthetic efficiency	*Environmental Pollution*	86	14.3
Gambardella et al. *(2018)*	Ecotoxicological effects of polystyrene microbeads in a battery of marine organisms belonging to different trophic levels	*Marine Environmental Research*	84	12.0

3.6Polymeric classes of microplastics studied

Among the polymer types investigated, polystyrene (PS) and polyethylene (PE) were the most frequently examined in experimental studies, appearing in 35 and 20 publications, respectively (Fig. 3). These were followed by polyvinyl chloride (PVC; 7 studies) and polypropylene (PP; 6 studies), while polyethylene terephthalate (PET) and polymethyl methacrylate (PMMA) were each addressed in four publications. This distribution closely aligns with environmental monitoring data, which identify PE, PP, PS, PVC, and polyamide as among the most prevalent polymers across global marine ecosystems (Cunha et al. 2019; Guo et al. 2020; Zhu et al. 2020; Wang et al. 2020; Nava and Leoni 2021; Wang et al. 2025b).

The overrepresentation of PS in toxicological assays—despite PE and PP often being found in higher concentrations in surface waters—likely results from the commercial availability in standardized spherical forms (e.g., microbeads), which facilitates experimental reproducibility. However, the high frequency of PVC and PET in recent studies indicates a shift toward investigating polymers with different densities and chemical additives, contributing to a more comprehensive understanding of how varying plastic compositions influence microalgal physiology.This pattern has important implications for ecotoxicological interpretation, as experimental studies may not fully represent the polymer composition typically found in natural marine environments.

Figure 3. Polymer types of microplastics investigated in experimental studies evaluating their effects on marine microalgae (n = 54).



3.7 Marine microalgae studied

The marine microalgae investigated across the selected studies were distributed among six taxonomic classes (Table 5). Bacillariophyta (diatoms) represented the largest proportion (38.30%), followed by Dinophyta (36.17%) and Chlorophyta (17.02%). Cryptista accounted for 4.25%, while Heterokontophyta and Haptophyta each represented 2.13%. This distribution reflects the ecological prominence of diatoms and dinoflagellates in marine ecosystems and underscores their established role as model organisms in ecotoxicological research. Their frequent selection is largely due to their fundamental contributions to global primary productivity, nutrient cycling, and bloom dynamics (Oliveira et al. 2020; Naselli-Flores 2023).

The high representation of *Bacillariophyta* and *Dinophyta*reflects the research focus on the most abundant and diverse phytoplankton groups in coastal and oceanic waters. However, the relatively low percentage of other taxa, such as *Haptophyta*, suggests a potential knowledge gap in understanding the impacts of MPson other ecologically significant groups, such as coccolithophores, which play a critical role in the marine calcium carbonate cycle. Expanding the taxonomic diversity in future experimental designs will be vital for a more holistic assessment of microplastic-induced shifts in marine community structures.

Table 5. Taxonomic groups and species investigated in studies on microplastic toxicity in marine microalgae (n = 54).

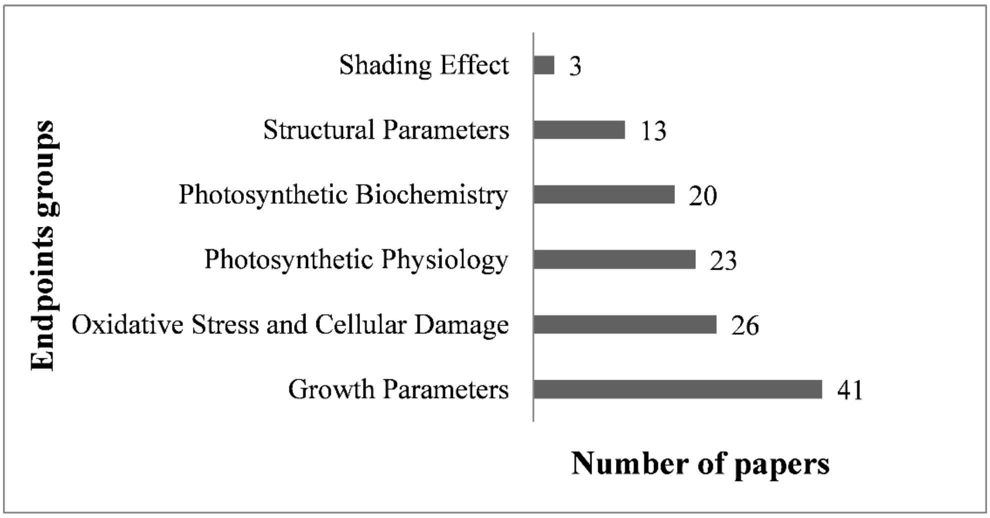
Classification	Species studied	References
Dinophyta	*Alexandrium* sp., *Ceratium*sp., *Prorocentrum*sp., *Gambierdiscus*sp., *Ostreopsis cf. ovata*, *Prorocentrum lima*, *Prorocentrumdonghaiense*, *Heterocapsa triquetra*, *Akashiwo sanguinea*, *Kareniamikimotoi*, *Prorocentrummicans*, *Prorocentrum minimum*, *Alexandrium tamarense*, *Gymnodinium aeruginosum*, *Gymnodinium* sp.	Long et al. 2017; Cunha et al. 2019; Zhao et al. 2019; Huang et al. 2021; Nava and Leoni 2021; Ge et al. 2022; Leite et al. 2022; Liu et al. 2022; Zhang et al. 2022; Li et al. 2023; Li et al. 2024;Xu et al. 2024; Pires et al. 2025; Wang et al. 2025a, c
Bacillariophyta	*Achnantes*sp., *Amphora* sp., *Cocconeis* sp., *Navicula* sp., *Skeletonema costatum*, *Pseudo-nitzschia pungens*, *Thalassiosira pseudonoma*, *Thalassiosira weissflogii*, *Chaetoceros neogracile*, *Chaetoceros calcitrans*, *Chaetoceros* sp., *Skeletonema* sp., *Amphora coffeaeformis*, *Chaetoceros gracilis*, *Thalassiosira* sp., *Nitzschia closterium f. minutissima*, *Chaetoceros curvisetus*	Sjollema et al. 2016; Long et al. 2017; Zhang et al. 2017; Seoane et al. 2019; Baudrimont et al. 2020; Feng et al. 2020; Guo et al. 2020; Wang et al. 2020; Zhu et al. 2020; Nava and Leoni 2021; Niu et al. 2021; Hao et al. 2022; Lang et al. 2022; Ni et al. 2023; Podbielska et al. 2023; Senousy et al. 2023; Chen et al. 2024; Lim et al. 2024; Lv et al. 2024; Mojiri et al. 2024; Wang et al. 2024; Wang et al. 2025a, c

Chlorophyta	*Dunaliellatertiolecta, Dunaliella salina, Tetraselmis chuii, Tetraselmis* sp., *Chlamydomonasreinhardtii, Raphidocelissubcapitata, Tetraselmis helgolandica var. tsingtaoensis, Platymonashelgolandica*	Sjollema et al. 2016; Gambardella et al. 2018; Prata et al. 2018; Chae et al. 2019; Cunha et al. 2019; Li et al. 2021; Podbielska et al. 2023; Liu et al. 2024
Heterokontophyta	*Heterosigmaakashiwo, Phaeodactylumtricornutum*	Wang et al. 2020; Ge et al. 2022; Sheng et al. 2023; Lim et al. 2025; Wang et al. 2025a
Cryptista	*Rhodomonas lens, Rhodomonas salina*	Pinto et al. 2023; Laranjeiro et al. 2024; Sioen et al. 2024
Haptophyta	*Isochrysisgalbana; Tisochrysis lutea*	Fernández et al. 2022; Jin et al. 2024; Meng et al. 2024; Wang et al. 2025a; Zhao et al. 2025;

3.8 Endpoints studied

Understanding which biological endpoints are most frequently evaluated in experimental microalgal toxicity studies is essential for improving ecotoxicological test design and ecotoxicological evaluation. Therefore, the endpoints reported in the selected studies were systematically categorized to identify dominant response parameters and underexplored indicators of microplastic toxicity. The endpoints reported across the selected studies were grouped into six functional categories based on biological response and analytical focus (Fig. 4): (1) shading effects; (2) structural parameters (morphology, sinking rate, and aggregate formation); (3) photosynthetic biochemistry (chlorophyll a, b, c, and carotenoids); (4) photosynthetic physiology (efficiency, photochemistry, chlorophyll autofluorescence, and relative electron transfer); (5) cellular stress and damage indicators (oxidative stress, esterase activity, membrane permeability, and DNA damage); and (6) growth parameters (inhibition, cell density, growth rate, and cell viability).

Figure 4. Biological endpoints evaluated in experimental studies on microplastic toxicity in marine microalgae (n = 54). Endpoints were grouped into six functional categories: (1) shading effects; (2) structural parameters (morphology, sinking rate, aggregate formation); (3) photosynthetic biochemistry (chlorophyll a, b, c, carotenoids); (4) photosynthetic physiology (efficiency, photochemistry, chlorophyll autofluorescence, relative electron transfer); (5) cellular stress and damage (oxidative stress, esterase activity, membrane permeability, DNA damage); and (6) growth parameters (inhibition, cell density, growth rate, viability).



Growth parameters represented the most frequently investigated endpoint group, addressed in 41 studies (Fig. 4). Within this category, 27 articles reported growth inhibition, while three observed no effect. Regarding growth rate, six studies identified significant effects, whereas five reported no changes. The data suggest that particle size may influence toxicity mechanisms: smaller particles exhibit higher toxicity due to greater penetration and surface adsorption (Chae et al. 2019; Wang et al. 2024), while larger particles primarily induce growth inhibition via shading effects (Zhang et al. 2017; Guo et al. 2020), and through restricted gas exchange (Zhang et al. 2017;Fu et al. 2019).

Cellular stress and damage indicators followed as the second most investigated group (26 studies) (Fig. 4). Oxidative stress responses were reported in 16 studies, although five studies found no such response, potentially due to variations in MPs concentrations and experimental conditions. Furthermore, research has identified structural damage to intracellular organelles and reductions in esterase activity and neutral lipid production (Mao et al. 2018; Seoane et al. 2019; Wang et al. 2024). The increasing focus on oxidative stress in recent years (e.g., Wang et al. 2025a, c; Zhao et al. 2025) reflects a shift toward understanding the sub-lethal biochemical pathways of plastic toxicity.

Photosynthetic physiology wasevaluated in 23 studies (Fig. 4). Toxic effects on photosynthetic rate were reported in five studies, whereas two studies observed no significant effects. Effects on photosynthetic efficiency were identified in ten studies, and alterations in chlorophyll autofluorescence were reported in two studies. Studies by Prata et al. (2018), Fu et al. (2019), and Wang et al. (2024) demonstrated that microplastic exposure may impair microalgal photosynthesis, resulting in reduced chlorophyll content and photosynthetic efficiency. Zhao et al. (2019) reported that micro-PVC MPs affected chlorophyll content, photosynthetic efficiency, and cell density in the dinoflagellate *Kareniamikimotoi*. In contrast, Chae et al. (2019) observed an increase in chlorophyll content when microalgae were exposed to high MPs concentrations.

Photosynthetic biochemistry was assessed in 20 studies (Fig. 4), with significant effects reported in 15 studies, while five studies observed no effects. Structural parameters were evaluated in 13 studies. Guschina et al. (2020) demonstrated that MPs may alter lipid and fatty acid composition in the microalga *Chlorella sorokiniana*, corroborating findings reported by Guo et al. (2020) for *Phaeodactylumtricornutum*. These results raise important questions regarding the impacts of MPs on microalgal biomolecule production and the transfer of essential lipid compounds across trophic chains, highlighting the need for further investigation.

Regarding aggregate formation, Jin et al. (2024) reported that aggregation between MPs and microalgae can induce shading effects, reducing photosynthetic efficiency and, consequently, microalgal growth. Shading effects were reported in only three studies, which demonstrated that MPs can induce growth inhibition, morphological alterations such as pyrenoid whitening, distorted thylakoids, damaged cell membranes, and cell wall thickening, as well as reductions in photosynthetic activity (Mao et al. 2018; Chae et al. 2019; Li et al. 2024). Additionally, MPs were shown to modulate energy metabolism by decreasing lipid-producing cells (Seoane et al. 2019).

Among the 54 studies evaluating the toxic effects of MPs on marine microalgae, only one study integrated laboratory findings with field-based analyses, including the identification and quantification of MPs (sizes 1.01 to 4.75 mm) in global surface waters. This study assessed the role of floating plastics as vectors for toxin transfer to three benthic dinoflagellate species: *Gambierdiscus* spp., *Ostreopsis* cf. *ovata*, and *Prorocentrum lima*. Distribution analysis indicated elevated relative risks of plastic colonization in the Mediterranean Sea and along subtropical and temperate western ocean margins, such as the eastern coasts of North America and Asia, and to a lesser extent, in southern Brazil and Australia (Leite et al. 2022).

Overall, the effects of MPs—whether acting alone or synergistically with other contaminants—on growth inhibition, chlorophyll *a* content, cell density, oxidative stress, and photosynthetic efficiency are well-documented and represent the most established parameters in the literature. In contrast, critical endpoints such as sinking rate, shading effects, aggregate formation, DNA damage, relative electron transfer, and immunological activity remain significantly under-explored. Furthermore, several studies report transient effects, where an initial period of physiological vulnerability is followed by adaptive responses leading to physiological recovery (Prata et al. 2019). These patterns may reflect intrinsic organismal resilience or shifts in MPs bioavailability within exposure media over time. These findings highlight the importance of quantifying MPs bioavailability and distribution within experimental frameworks. Achieving accurate estimates of the effective exposure concentrations is vital for bridging the gap between controlled laboratory settings and the complex dynamics of marine environments (Long et al. 2017).

Despite the rapid increase in experimental studies addressing microplastic toxicity in marine microalgae, many investigations still rely on simplified laboratory exposure scenarios that may not reflect environmentally realistic conditions. Frequently used particle types, concentrations, and size distributions often differ from those found in natural marine environments, potentially leading to an overestimation of ecological risks. Additionally, variability in experimental design, including differences in particle size, polymer type, and exposure conditions, limits comparability across studies. These findings highlight the need for standardized experimental approaches and environmentally realistic exposure scenarios to improve the reliability of experimental ecotoxicological frameworks.This integrative perspective highlights the importance of linking experimental endpoints with mechanistic pathways to better understand the environmental relevance of microplastic toxicity.

Because marine microalgae constitute the base of aquatic food webs, alterations in their physiology and growth may potentially influence trophic transfer processes and the movement of MPs through marine food chains. Overall, the available evidence indicates that while several key physiological endpoints of microplastic toxicity in marine microalgae are increasingly well documented, important knowledge gaps remain regarding environmentally realistic exposure scenarios and underexplored biological responses.Collectively, these findings suggest that microplastic exposure may influence key physiological processes that regulate marine primary productivity, potentially affecting energy transfer and trophic dynamics within aquatic ecosystems.

4. Conclusion

This review synthesizes current knowledge on interactions between microplastics and marine microalgae, highlighting the rapid expansion of this field over the past decade. The available scientific literature suggests that microplastics may negatively affect marine microalgae through multiple physiological pathways, particularly growth inhibition, oxidative stress, and alterations in photosynthetic performance. These responses may have broader ecological implications given the central role of microalgae in marine primary productivity and nutrient cycling. From an ecotoxicological perspective, these findings highlight which biological endpoints currently provide the strongest evidence of microplastic toxicity in primary producers and which parameters require further experimental validation.

The analysis also reveals that research is concentrated within a limited number of countries and journals, indicating an uneven global research landscape. In addition, most studies rely on short-term laboratory experiments using simplified exposure scenarios and a limited range of polymer types, primarily polystyrene and polyethylene. Although these approaches have improved understanding of cellular and physiological responses, they provide limited insight into ecosystem-level consequences.

Important knowledge gaps remain regarding environmentally relevant processes such as microplastic–microalgae aggregation, particle sinking dynamics, DNA damage, and long-term exposure under environmentally realistic concentrations. Addressing these gaps will be essential for improving the ecological relevance of future studies.

Collectively, this study contributes to advancing current understanding of microplastic toxicity in marine microalgae by integrating experimental evidence with environmental relevance. The findings emphasize the importance of standardized methodologies, environmentally realistic exposure conditions, and the inclusion of underexplored biological endpoints to improve experimental ecotoxicological approaches and interpretation of microplastic toxicity. By providing an evidence-based synthesis, this work contributes to future research aimed at bridging laboratory findings with real-world environmental conditions and improving the assessment of microplastic impacts on marine ecosystems.

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Declarations

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Authors' Contributions

All authors contributed to the study conception and design. Nágela G. R. dos Santos was responsible for investigation, resource, data curation, methodology, and drafting of the original manuscript. Késsia F. de B. Pinho contributed to data curation, formal analysis, writing review and editing. Itala de Cassia Sousa Reis contributed to the data curation, formal analysis, writing review and editing. Ricardo Luvizotto-Santos contributed to supervision, writing review and editing. Marianna Basso Jorge contributed to funding acquisition, project administration, supervision, writing review and editing. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Data Availability Statement

All data generated or analyzed during this study are included in this published article and its supplementary information files. The dataset used for literature synthesis and evidence mapping is provided in Supplementary Table S1.

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Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Supplementary Information

Additional data are available in Excel format and include the table of selected articles (n = 54) used for the literature synthesis and evidence mapping presented in this study (Supplementary Table S1).