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A critical synthesis of seagrass meadows as microplastic sinks: current trends and research gaps

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Abstract. Seagrass meadows are increasingly being recognized as accumulation zones for microplastics. To critically evaluate this role, this systematic review analyzed 84 peer-reviewed studies published between 2015 and 2024, identified through the Scopus database using the PRISMA guidelines. These findings indicate that dense seagrass canopies attenuate hydrodynamic forces, and epiphytic biofilms enhance particle adhesion, leading to significantly higher microplastic concentrations in sediments (ranging from 1.3 to 17.6 times) than in adjacent unvegetated areas. This sequestration creates a scenario in which high biodiversity habitats overlap with elevated contaminant exposure, increasing the risk of ingestion by seagrass-associated fauna and facilitating trophic transfer into coastal food webs. However, seagrasses are not permanent sinks; storm-driven resuspension and detritus export can remobilize plastics, making meadows a secondary source. This review emphasizes the dual role of seagrasses as filters and vectors for microplastic pollution. Effective management must conserve these habitats to maintain their filtering function, while urgently addressing plastic inputs at their sources and exploring long-term impacts on seagrass health.

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Keywords: Seagrass meadows, microplastics, bibliometric analysis, ecological trap, marine pollution

1 Introduction

Seagrass meadows are vital coastal ecosystems that provide a wide array of ecological services that make them essential for marine and coastal health [1]. These habitats play a key role in carbon sequestration, with seagrass meadows storing carbon in both their biomass and sediments at rates much higher than terrestrial forests, a process known as "blue carbon" [2]. In addition, seagrass meadows help stabilize coastal sediments and reduce shoreline erosion by acting as natural barriers to wave energy and tidal forces [3]. Their dense root and rhizome systems also support biodiversity by creating complex habitats for numerous marine species, including commercially important fishes, crustaceans, and mollusks [4]. Seagrass beds are not only critical for supporting marine life but also provide ecosystem services such as nutrient cycling, water filtration, and refuge for juvenile marine organisms [4].

In recent years, seagrasses have been increasingly recognized for their role in mitigating marine pollution, as they can trap and retain contaminants from surrounding waters, including excess nutrients, sediments, and potentially harmful pollutants such as microplastics [5]. Microplastics, defined as plastic particles less than 5 mm in size, have become one of the most pervasive pollutants in the ocean owing to their small size, durability, and ability to persist in the environment [5]. These particles originate from the fragmentation of larger plastic debris, such as plastic bottles, bags, and fishing nets, which break down into smaller particles over time owing to physical, chemical, and biological processes [6]. Another significant source of microplastics is the shedding of synthetic fibers from textiles during washing, which are released into wastewater systems and eventually enter marine environments [6].

The widespread distribution of microplastics in marine ecosystems, ranging from surface waters to the deep sea, has raised alarms because of their potential to harm marine organisms and ecosystems. Once in the environment, microplastics are easily ingested by a wide range of marine organisms, from plankton to larger fish and mammals, leading to potential physical damage, chemical exposure, and trophic transfer [7]. The hydrophobic nature of microplastics allows them to adsorb persistent organic pollutants (POPs) from the surrounding water, which can further increase toxicological risks when ingested by marine organisms [8]. Furthermore, microplastics can disrupt feeding behavior, cause internal injury, and impair growth and reproduction in marine species, highlighting the need for a better understanding of their impact on marine food webs [9–11].

Seagrass meadows, owing to their physical structure and ecological role, have been identified as significant "sinks" for microplastics, where particles accumulate at high concentrations in the sediment and on seagrass surfaces [5]. The dense canopy of seagrass acts as a natural filter, capturing suspended particles in the water column, whereas biofilms on the surface of seagrass leaves enhance the adhesion of microplastics, particularly fibers, which are more likely to adhere to the biofilm matrix [5]. Studies have shown that microplastic concentrations in seagrass meadows are often orders of magnitude higher than those in adjacent unvegetated areas, thereby emphasizing their role in trapping microplastics[5]. However, this retention capacity is not uniform; it is heavily influenced by local hydrodynamic energy and the physical properties of the plastic, such as polymer density, which dictate whether particles settle or remain in suspension. This accumulation presents an ecological paradox, as seagrass meadows, while providing important filtration services, may inadvertently expose marine organisms to higher concentrations of plastic debris, thereby leading to potential ecological and health risks.

Although previous reviews have qualitatively discussed these filtration services, there is a lack of systematic analysis combining mechanistic insights with global research trends. Therefore, this study aims to fill this gap with two specific objectives: (i) to provide a critical synthesis of the mechanisms driving microplastic accumulation and their ecological consequences, specifically the "ecological trap" phenomenon; and (ii) to conduct a reproducible bibliometric analysis to map the evolution of the field and identify key geographic biases and knowledge gaps.

2 Methodology

2.1 Search strategy and data sources

This systematic review and bibliometric analysis followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility. A comprehensive literature search was performed using the Scopus database. Scopus was selected for its extensive coverage of high-impact peer-reviewed journals on marine science and environmental studies [12]. While Scopus provides broad coverage, we acknowledge a potential geographical bias as it may exclude some regional or local journals not indexed in the database.

The search was executed on August 19, 2025, covering the publication period 1986 to 2024. To ensure the retrieval of all relevant studies, a specific search string combining keywords for plastic pollution (e.g., "microplastic," "nanoplastic") and seagrass genera (e.g., Zostera, Posidonia, Enhalus) was employed. The search was restricted to English-language documents including Articles, Review Articles, Conference Papers, and Book Chapters. The detailed protocol for reproducing this search is presented in **Table 1**.

Table 1. Search strategy and reproducibility protocol employed for the data retrieval process.

Parameter	**Description**
Database source	Scopus (Elsevier)
Date of search	19 August 2025
Time span	1986 – 2024 (inclusive)
Language	English
Document types	Article (ar), Review (re), Conference Paper (cp), Book Chapter (ch)
Search string	TITLE-ABS-KEY (("microplastic*" OR "microplastics*" OR "plastic pollution" OR "plastic particles" OR "plastic fibers" OR "nanoplastics" OR "plastic debris" OR "plastic waste" OR "plastic") AND ("seagrass" OR "seagrass*" OR "seagrass bed*" OR "seagrass meadow*" OR "seagrass ecosystem" OR "seagrass habitat" OR "Phyllospadix" OR "Zostera" OR "Enhalus" OR "Halophila" OR "Thalassia" OR "Posidonia" OR "Amphibolis" OR "Cymodocea" OR "Halodule" OR "Syringodium" OR "Thalassodendron" OR "Ruppia")) AND PUBYEAR > 1985 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English"))
Final selection	84 documents (after screening)

2.2 Screening and selection process

The selection process followed a multi-stage screening workflow, as depicted in **Fig. 1**. The initial keyword search yielded 283 articles. The records were exported to Microsoft Excel for deduplication and screening. Although Scopus generally filters duplicates, a manual check was performed to ensure data integrity.

First, the records were filtered based on metadata criteria, excluding 37 documents that fell outside the scope of the study. The remaining 246 records were subjected to manual screening of titles and abstracts. To minimize bias, screening was conducted by the primary author, with uncertainties regarding inclusion resolved through consultation and consensus with the co-authors. Articles were excluded if they: (i) focused solely on macrodebris without discussing microplastics, (ii) mentioned seagrass only as a substrate for non-pollution studies, or (iii) were laboratory-only studies using polymer types irrelevant to marine environments. Rigorous content screening led to the exclusion of 162 articles. A final total of 84 articles were selected for the bibliometric and qualitative synthesis.

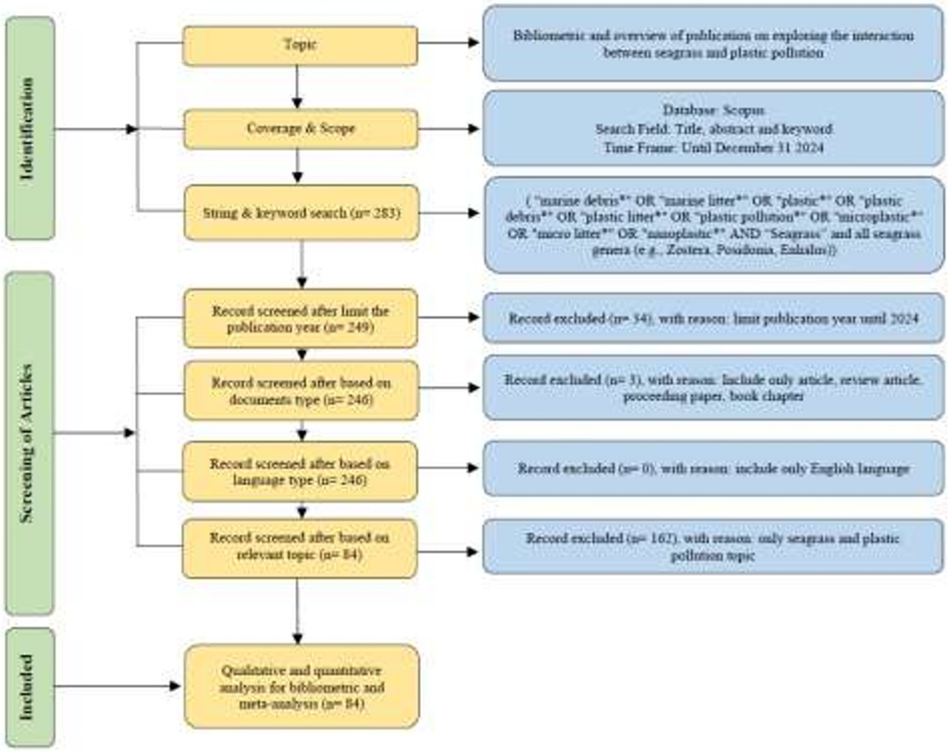

Fig. 1. The PRISMA flowchart describing the data collection and screening procedure.

2.3 Data extraction and bibliometric analysis

Bibliometric data (including authors, affiliations, citations, keywords, and publication year) from the selected 84 articles were exported in the BibTeX and CSV formats. Data cleaning was performed using Microsoft Excel to standardize terms (e.g., merging synonyms such as "micro-plastic" and "microplastics") and correct inconsistent author names or journal abbreviations. The cleaned dataset was analyzed using the bibliometrix R package (version 4.1) via the biblioshiny web interface. This software was used to map research trends, visualize keyword co-occurrence networks, and identify collaboration patterns. Self-citations were retained to reflect the total activity and interconnectedness of the research fields.

3 Result and discussion

3.1 Performance analysis

The first step in this study was to conduct a research performance analysis to identify developments and provide an overview of research on the interaction between seagrass and plastic pollution. Between 2015 and 2024, 84 publications were published on the interaction between seagrass meadows and plastic pollution, with an annual growth rate of 40.25%. These publications involved 396 authors and were sourced from 27 journals, accumulating 3,179 citations, with an average of 37.85 citations per document, reflecting the academic significance of the topic (**Table 2**). The body of research is steadily growing, yet the total volume of publications remains moderate, indicating the subject's increasing attention but not yet high research output. Regarding document type, the majority were journal articles, comprising 58 documents or 69.05% of the total, followed by 14 review papers (16.67%), 11 conference papers (13.10%), and one book chapter (1.19%) (**Fig. 2**). Despite the moderate number of publications, the high citation impact suggests that the research produced was of significant value. This growth in publications and citations highlights the increasing recognition of the importance of understanding the seagrass-plastic pollution interaction, although further studies are needed to explore the ecological impacts and effectiveness of seagrass restoration efforts in mitigating plastic pollution.

Table 2. Main statistics and descriptive characteristics of the analyzed dataset regarding seagrass ecosystems and plastic contamination.

Component	Description	Result
Publication	Total number of research publications	84
Publication period	Period Active period of research publications	2015:2024
Productivity	Annual growth rate (%)	40.25
Source	Total number of journal sources in related fields	27
Total citation	Total citation in all publication	3,179
Average Citations per Document	Total citation/publication	37.85
Total Author	Total research authors contributing to the field	396
Author's Keywords	Total publication keywords	255

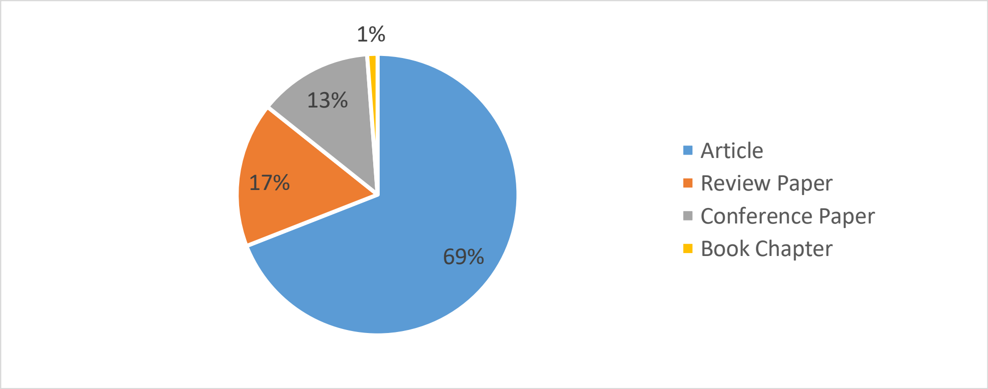

Fig. 2. Classification of the analyzed publications based on document type from 2015 to 2024.

3.2 Annual scientific production

Fig. 3 depicts the exponential growth in yearly publications on the interaction between seagrass meadows and plastic pollution from 2015 to 2024. The data are best described by a second-order polynomial regression (dashed line), which yielded a high coefficient of determination (R^2) of 0.89. This value indicates that the model explained approximately 89% of the variance in publication growth. This trend reveals a distinct pattern: a relatively slow accumulation of studies between 2015 and 2019, followed by a marked inflection point around 2020, where research output accelerated significantly. Despite a minor fluctuation in 2022, the overall trajectory demonstrates a sharp upward surge, reflecting the rapidly growing attention of the scientific community towards this emerging environmental issue.

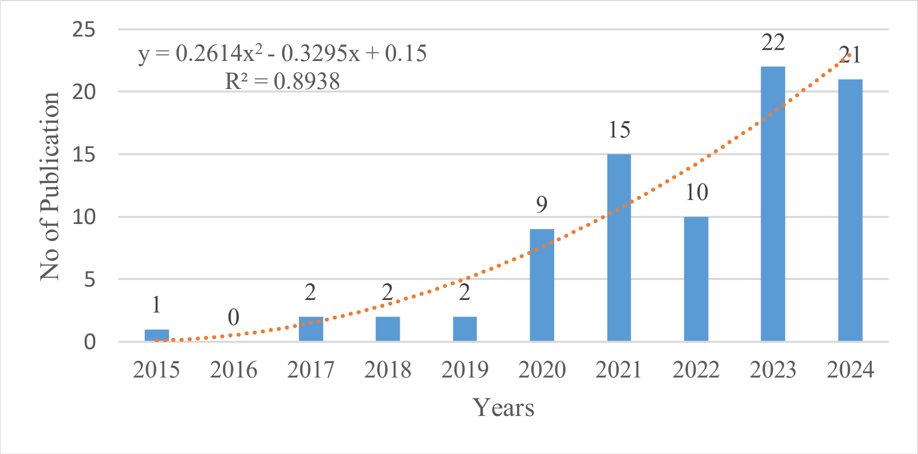

Fig. 3. Annual publication trend from 2015 to 2024.

3.3 Most relevant journals

Bibliometric data on the interaction between seagrass meadows and plastic pollution highlight significant contributions from various journals (**Table 3** and **Fig. 4**). The performance of these sources was evaluated based on the total articles, total citations (TC), and h-index, calculated using the biblioshiny interface based on Scopus citation data accumulated up to the cut-off date of August 19, 2025. The Marine Pollution Bulletin has 17 articles, 789 citations, and an h-index of 13, indicating a strong influence in the field. Science of the Total Environment follows 13 articles, 635 citations, and an h-index of 12, showing substantial contributions. Environmental Pollution has published nine articles with 491 citations and an h-index of 7, while the IOP Conference Series: Earth and Environmental Science (7 articles, 76 citations, h-index 4) and Environmental Science and Pollution Research (6 articles, 75 citations, h-index 4) also contributed significantly. Other sources, such as Environmental Science and Technology (4 articles, 546 citations, h-index 4) and Marine and Freshwater Research (2 articles, 130 citations, h-index 2), reflect focused but meaningful engagement. Journals such as the Journal of Physics: Conference Series, Marine Environmental Research, and Regional Studies in Marine Science each published two articles, contributing a total of 9–130 citations and an h-index of 2, highlighting diverse research across environmental science disciplines. While the majority of sources published fewer articles, their citation impact and h-indices demonstrated their significant role in advancing research on plastic pollution and its interaction with seagrass meadows.

Table 3. Top ten most productive Journals and their Citations and H-Index.

No.	Sources	Articles	Total Citation	H-Index
1	Marine Pollution Bulletin	17	789	13
2	Science of the Total Environment	13	635	12
3	Environmental Pollution	9	491	7
4	IOP Conference Series: Earth and Environmental Science	7	76	4
5	Environmental Science and Pollution Research	6	75	4
6	Environmental Science and Technology	4	546	4
7	Marine and Freshwater Research	2	130	2
8	Journal Of Physics: Conference Series	2	66	2
9	Marine Environmental Research	2	11	2
10	Regional Studies in Marine Science	2	9	2

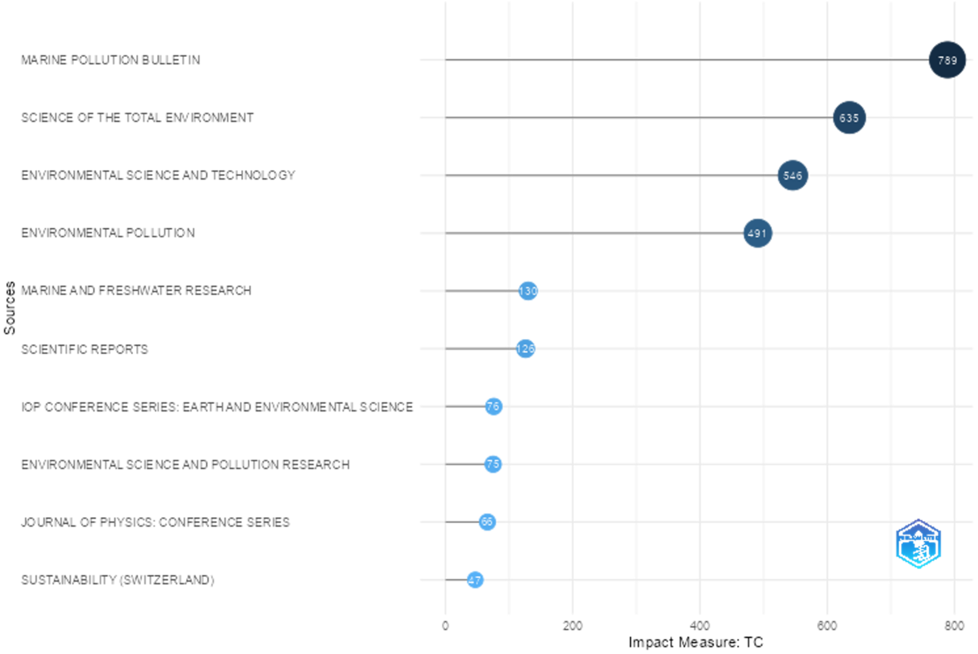

Fig. 4. Top ten most cited journals.

3.4 Most relevant countries

Based on the analysis of the corresponding authors' affiliations, research on the interaction between seagrass meadows and plastic pollution has attracted significant international attention, involving contributors from 32 countries. As detailed in **Table 4**, leading countries exhibit a diverse mix of productivity and citation impact.

The countries leading to research on the interaction between seagrass meadows and plastic pollution exhibit a diverse mix of productivity and citation impacts (**Table 4** and **Fig. 5**). Italy is the highest producer of publications, with 11 articles and 451 total citations, whereas China has the highest citation count, with 533 citations from 10 articles. Other significant contributors include Indonesia, which produced 10 articles and received 118 citations, and Spain, with 8 articles and 237 citations. Despite having fewer publications, Portugal (three articles) has a strong citation count of 230, reflecting its relevance in the field. Australia, Singapore, the United Kingdom, and the USA have made notable contributions, with the USA having five articles and 282 citations, underscoring its active engagement in seagrass and plastic pollution research.

Fig. 3 shows the distribution of single-country publication (SCP) and multi-country publication (MCP) collaborations among these nations. Italy leads in SCP with eight articles but also has a significant proportion of MCP (three articles), indicating strong international collaboration. China, while highly productive, exhibits a more balanced distribution, with six articles in the SCP and four in the MCP. Indonesia has a dominant focus on SCP, contributing nine articles in this category, with minimal MCP involvement. The United Kingdom stands out with 60% of its articles (3) being part of the MCP, demonstrating its active participation in global research efforts. Portugal, Tunisia, and other smaller contributors mostly have higher involvement in MCP (up to 100% in some cases), which highlights their collaborative nature, despite having fewer publications.

Table 4. Highest producing and cited nation

Highest Producing Nations		
Country	**Articles**	**Citations**
Italy	11	451
China	10	533
Indonesia	10	118
Spain	8	237
Australia	5	47
Singapore	5	137
United Kingdom	5	169
Usa	5	282
Portugal	3	230
Tunisia	3	19

Highest Cited Nations		
Country	**Citations**	**Articles**
China	533	10
Italy	451	11
Usa	282	5
Spain	237	8
Portugal	230	3
United Kingdom	169	5
Singapore	137	5
Indonesia	118	10
Norway	110	1
Sweden	101	1

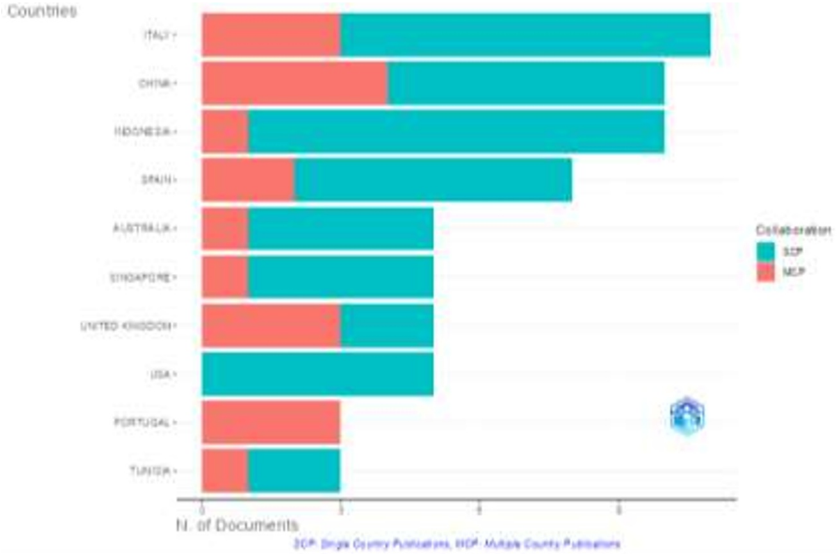

Fig. 5. MCP and SCP collaboration.

3.5 Most relevant documents

The diagram presented in **Fig. 6** illustrates the fundamental structure of documenting citations in seagrass and plastic pollution-focused research. This visual aid facilitates assessment of the proportion of highly cited documents, enabling comparisons among different publications.

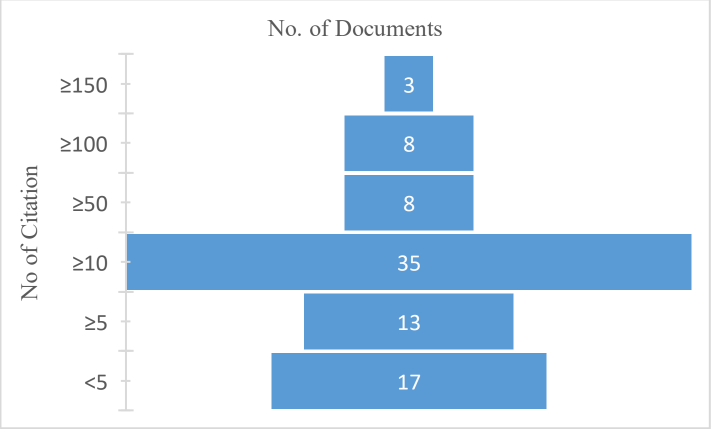

Fig. 6. Basic structure of citations of documents.

The analysis of the citation distribution in this study revealed a more balanced pattern across the examined documents. Specifically, three documents (3.6%) received 150 or more citations, eight documents (9.5%) received 100 or more citations, and another eight documents (9.5%) received 50 or more citations, indicating a moderate to high level of scholarly attention. A significant proportion (35 documents, 41.7%) received 10 or more citations, while 13 documents (15.5%) had five or more citations. However, 17 documents (20.2%) received fewer than 5 citations, suggesting that some publications were either recent or had a narrower scope of influence. Overall, the citation distribution is relatively even, with a steady level of scholarly engagement across the body of work, indicating that the field is steadily growing, and citations are likely to increase as these works gain more recognition over time.The top ten most frequently cited documents, along with their key highlights, are presented in **Table 5**.

Table 5. Top ten most relevant documents on seagrass and plastic pollution.

No	Reference	DOI	Key Highlight	Total Citations	TC/ Years
S	Remy F, 2015, Environ Sci Technol	10.1021/acs.est.5b02005	Invertebrates in *Posidonia oceanica* litter ingest artificial fibers, primarily viscose, with industrial dyes like Direct Blue 22 and Direct Red 28.	320	32
2	Goss H, 2018, Mar Pollut Bull	10.1016/j.marpolbul.2018.08.024	Seagrass *Thalassia testudinum* in Turneffe Atoll accumulates microplastics, primarily microfibers. Seventy-five percent of blades had encrusted microplastics, suggesting macroherbivory as a pathway for microplastic pollution to enter marine food webs.	179	25.6

No	Reference	DOI	Key Highlight	Total Citations	TC/ Years
3	Huang Y, 2020, Environ Pollut	10.1016/j.envpol.2019.113450	This study quantifies microplastics, primarily fibers, in seagrass meadows (*Enhalus acodoides*) and bare sites in Xincun and Li'an bays, China, showing non-selective enrichment in seagrass sediments regarding shape, color, or size.	176	35.2
4	Sanchez-Vidal A, 2021, Sci Rep	10.1038/s41598-020-79370-3	Seagrass meadows trap and aggregate plastic debris with natural fibers, including up to 1,470 plastic items per kg of plant material. This process helps counteract marine plastic pollution, highlighting the ecological importance of seagrass in mitigating plastic contamination.	126	31.5
5	Cozzolino L, 2020, Sci Total Environ	10.1016/j.scitotenv.2020.138018	Coastal vegetated habitats, including seagrasses and saltmarshes, trap macro and microplastics at varying degrees. Microplastics, primarily fibers, accumulate more in subtidal habitats, with significant variability in trapping effectiveness	125	25
6	Ouyang X, 2022, Environ Sci Technol	10.1021/acs.est.1c06732	Seagrass meadows trap plastics, with lower plastic abundance in sediments and ingestion by marine animals compared to mangrove forests and tidal marshes, highlighting their role in plastic pollution.	110	36.7
7	Harris Pt, 2021, Sci Total Environ	10.1016/j.scitotenv.2021.145222	Seagrass habitats, located on wave-dominated coasts, receive 11.6% of river-borne plastic pollution, with 24.1% of seagrass areas being within 20 km of rivers discharging over 1 ton per year of plastic, highlighting the need for targeted monitoring and mitigation efforts.	110	27.5
8	Huang Y, 2021, Environ Sci Technol	10.1021/acs.est.0c07289	This study found significant microplastic accumulation in seagrass meadows dominated by *Halophila beccarii* and mangrove forests dominated by *Avicennia marina*, with microplastics enriched compared to unvegetated sites, and a strong positive correlation between microplastic abundance and particulate organic carbon content.	107	26.8

No	Reference	DOI	Key Highlight	Total Citations	TC/ Years
9	Jones Kl, 2020, Mar Pollut Bull	10.1016/j.marpolbul.2020.110883	This study is the first to document microplastic accumulation in *Zostera marina* beds, finding 280 microplastic particles (0.04 to 3.95 mm) in 94% of samples, with fibres contributing over 50% of the total, and successfully identifying 50 microplastics as plastic using ATR-FTIR.	107	21.4
10	Dahl M, 2021, Environ Pollut	10.1016/j.envpol.2021.116451	This study investigates microplastic contamination in *Posidonia oceanica* meadows along the Spanish Mediterranean coast, finding a significant increase in microplastics since the mid-1970s, particularly after the intensification of the agricultural industry in Almería, with the highest concentrations observed in recent surface soils and the highest accumulation rate in Roquetas.	101	25.3

3.6 Most frequent and trending keywords

This section aims to investigate the primary authors' keywords, their co-occurrences, and current trending keywords in the field of seagrass and plastic pollution research. This analysis used a dataset comprising 84 documents and 404 author keywords. Based on the frequency of occurrence, the majority of keywords had relatively low frequencies. Specifically, only two keywords (0.8%) appeared more than 20 times, three keywords (1.2%) appeared more than ten times, and five keywords (2.0%) appeared more than five times. The remaining 241 (96.0%) keywords appeared only once. These data indicate that the distribution of keywords within the dataset is highly dispersed, with a small number of keywords having high occurrences, which highlights the main topics of focus in this research field. A visual representation of the 20 most-utilized terms is shown in **Fig. 7**. The keyword "microplastic" appeared most frequently (37 times), followed by "seagrass" (25 times), "sediment" (15 times), and "marine litter" (10 times).

Fig. 7 displays the network of the most used author terms and their co-occurrence. To ensure clarity, the network was constructed using the Fruchterman-Reingold layout algorithm, with the minimum edge weight set to two and standard stopword removal applied. Each circle in the figure represents a specific author's keyword, where the size of the circle indicates frequency, and the connecting lines represent the strength of co-occurrence based on the Jaccard similarity coefficient. Circles sharing the same color denote the keyword clusters. Our analysis identified 27 keywords that occurred a minimum of two times, which were then categorized into six distinct clusters, each assigned a unique color. The blue cluster (the central cluster) represents the core focus of the research, dominated by the keywords "seagrass" and "microplastic." This cluster also includes related terms such as "marine pollution," marine plastic pollution, "Posidonia oceanica," Mediterranean Sea, "sediment," epiphytes, "photosynthesis," Bintan Island, "ingestion," and "coastal wetlands." These terms suggest a concentrated interest in studying the interaction between seagrass ecosystems and microplastic pollution, especially in the Mediterranean Sea. The presence of "epiphytes" and "photosynthesis" indicates a focus on the biological processes within seagrass beds affected by microplastics. The red cluster highlights keywords such as "marine litter," "plastic/pollution," "coastal ecosystems," "plastic," and "mangrove." mangroves. This cluster points to the broader environmental issue of plastic pollution and its impact on coastal environments, extending beyond seagrass ecosystems. The inclusion of "mangrove" suggests that research in this cluster also explores the effects of plastic pollution on other coastal ecosystems, specifically mangroves, indicating the widespread nature of the problem.

The green cluster was centered on the keywords "seagrass beds" and "marine debris," focusing on the physical components of seagrass habitats and the accumulation of debris within these ecosystems. The brown cluster, which includes terms such as "acid digestion," "NMR spectroscopy," and "stereomicroscopy," emphasizes the analytical methods used to study microplastic pollution. Finally, the purple cluster is focused on "P. oceanica" and "monitoring," implying research on the monitoring of Posidonia oceanica, a key seagrass species, to understand its condition in the face of environmental stressors like pollution. This network analysis offers insights into the relationships and co-occurrence among the most frequently used keywords, providing a comprehensive understanding of the key themes and concepts within the domain of study.

Furthermore, this section describes the prevailing keywords used in the study of seagrass and plastic pollution interactions. Our analysis reveals that the most frequently used keyword is "microplastic" (37 occurrences), which shows trending dominance starting around 2022. Following this are "seagrass" (25 occurrences) and "sediment" (15 occurrences), which became prominent topics in 2021. Other notable keywords include "marine pollution" and "plastic" (6 occurrences each), which first appeared in 2020. The terms "marine debris" (5 occurrences) and "plastic litter" (2 occurrences) emerged in 2022 and 2019, respectively, highlighting the ongoing concern over plastic waste in marine environments. Keywords such as "zostera marina" (2 occurrences) and "posidonia oceanica" (five occurrences) indicate a focus on a specific seagrass species, both first appearing in 2020 and 2022. Additionally, analytical methods like "acid digestion" and "distribution" (both 2 occurrences) emerged in 2024, reflecting the methodologies used in studying plastic pollution in seagrass ecosystems. This dataset emphasizes the growing research focus on understanding the interaction between seagrass ecosystems and plastic pollution, particularly microplastics and their effects on marine environments.

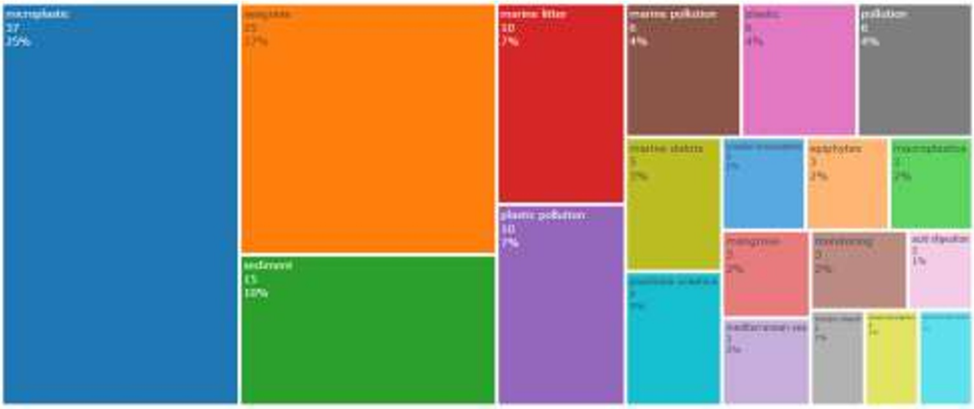

Fig. 7. Most frequent keywords.

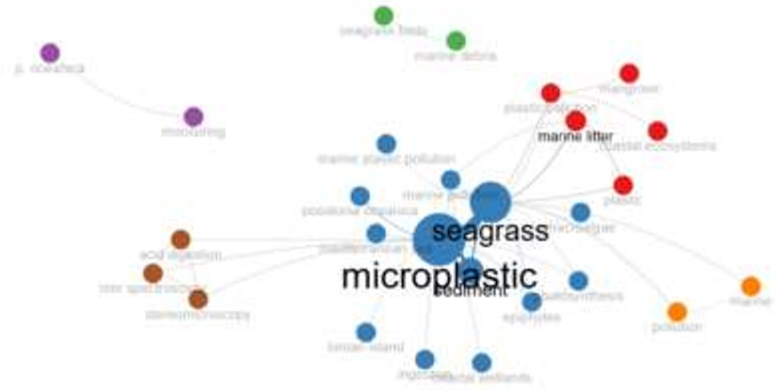

Fig. 8. Co-occurrence network of author's keywords.

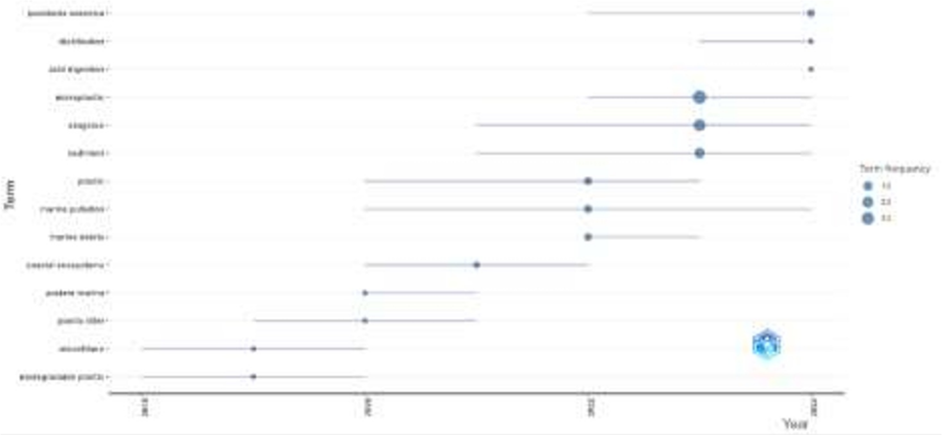

Fig. 9. Trending keywords of last ten year.

3.7 Repot finding on research of seagrass and plastic pollution interaction

3.7.1 Mechanisms of interaction

The capacity of seagrass meadows to trap and retain microplastics is primarily governed by physical processes analogous to those that make them effective sediment traps. The dense three-dimensional canopy structure of seagrasses acts as a baffle, reducing water flow velocities and attenuating wave energy. This alteration in local hydrodynamics enhances the gravitational settling of suspended particles, including MPs, leading to their accumulation in the underlying sediments. Numerous studies have documented this phenomenon, finding that MP concentrations in seagrass sediments are often significantly higher ranging from 1.3 to 17.6 times than those in adjacent unvegetated areas or the overlying water column [13]. This enrichment has been observed across diverse geographic regions, from *Zostera marina* beds in the Baltic Sea to meadows in the South China Sea, underscoring the global relevance of this trapping mechanism [14,15]. **Table 6** summarizes the variability of this enrichment factor across different studies and species, highlighting the influence of the local environmental settings.

Table 6. Synthesis of microplastic enrichment mechanisms in seagrass meadows.

Reference	Location / Species	Key Mechanism & Finding
[16]	South China Sea (*Enhalus acoroides*)	Sediment Trapping: Documented non-selective enrichment where seagrass sediments contained significantly higher MP abundance than bare sites, regardless of plastic shape or size.
[17]	United Kingdom (*Zostera marina*)	Canopy Retention: 94% of seagrass samples contained MPs. The canopy effectively trapped fibers (>50% of total), leading to concentrations significantly exceeding adjacent sediment.
[18]	Mediterranean (*Posidonia oceanica*)	Trapping & Export: Natural fiber aggregates (egagropiles) trap plastic debris (up to 1,470 items/kg). These egagropiles are ejected during storms, effectively cleaning the meadow but exporting plastic to beaches
[19]	Belize (*Thalassia testudinum*)	Biofilm Adhesion: 75% of seagrass blades had encrusted microplastics, highlighting the role of epiphytes and biofilms in capturing particles from the water column before they settle.
[20]	Portugal (*Zostera noltei*)	Hydrodynamic Filter: Demonstrated that subtidal meadows are more effective at trapping fibers than intertidal zones due to constant submersion and interaction with water flow
[13]	China (*Halophila beccarii*)	Carbon Coupling: Found a strong positive correlation between MP abundance and particulate organic carbon (POC), suggesting that mechanisms sequestering blue carbon also sequester plastics
[21]	Spain (*Posidonia oceanica*)	Long-term Sink: Analysis of soil cores revealed a historical accumulation of MPs since the 1970s, mirroring the intensification of local agricultural plastic use

Controlled hydraulic flume experiments provide direct mechanistic insight into this process [22]. The probability of MP retention is positively correlated with seagrass shoot density and the specific density of the plastic polymer, while it is negatively correlated with the velocity of water flow. These experiments revealed that denser, sinking particles (e.g., polystyrene, polyamide, and polyethylene terephthalate) are effectively trapped in scouring depressions that form around the base of seagrass shoots across a wide range of flow velocities. In contrast, buoyant floating particles (e.g., polypropylene) are typically retained only at low flow velocities, where a dense canopy can form a barrier at the surface of the water. The accumulation process is strongly linked to near-bed turbulent kinetic energy (TKE), confirming that the same hydrodynamic principles governing natural sediment deposition also dictate the fate of microplastics in these systems. This physical trapping is not limited to sediments; the fibrous remains of seagrasses, such as the well-known *Posidonia oceanica* spheroids (egagropiles), have been found to incorporate a high density of plastic items, effectively bundle them, and facilitate their removal from marine environments when washed ashore [23].

3.7.2 The role of biological factors

Beyond purely physical trapping, a suite of biological processes significantly enhances the retention of microplastics within seagrass ecosystems. The surfaces of seagrass blades are not inert, but are colonized by a complex community of epiphytes, including algae, bacteria, and invertebrates [24]. These epiphytic communities, along with the biofilms they produce, create a sticky textured surface that facilitates the adhesion of suspended MPs. Studies have documented MPs encrusted on the blades of various seagrass species, including *Thalassia testudinum* and *Zostera marina* [19,25]. The formation of biofilms on the surfaces of plastic particles is a critical factor. Epiphytic bacteria isolated from eelgrass leaves have been shown to accelerate biofilm formation on suspended polystyrene MPs. This process increases the particle density and promotes their aggregation into larger marine-snow-like flocs, which then sink more rapidly and become incorporated into the sediment. This biologically mediated sinking mechanism represents a key pathway for transferring MPs from the water column to benthos. Furthermore, exopolysaccharides (EPS), sticky substances secreted by macrophytes and their associated microbial communities, can act as natural "glue" [26]. Research has found a significant positive correlation between the amount of EPS on macrophyte surfaces and the level of MP contamination, suggesting that EPS enhances the capture and retention of plastic particles from water. The colonization of plastic debris by microbial communities, forming a distinct ecosystem known as the "plastisphere," is now recognized as a ubiquitous process in seagrass habitats. The composition of this plastisphere is heavily influenced by the surrounding sediment microbiome and often shows an enrichment of bacteria with potential plastic-degrading capabilities.

Although the mechanisms for MP trapping are well supported, the universal characterization of seagrass meadows as enhanced sinks is a matter of the complexity of the environment, with field evidence presenting a more complex and nuanced picture. Several studies comparing MP concentrations in seagrass sediments to those in adjacent unvegetated control sites have found no statistically significant differences in abundance [27]. This suggests that, in some contexts, MP contamination reflects a general build-up in a wider coastal environment rather than a specific, habitat-driven concentration effect. The resolution of this apparent conflict lies not in dismissing one set of findings but in recognizing that the trapping efficiency of a seagrass meadow is not a fixed attribute. Instead, it is a dynamic function that is highly dependent on a suite of interacting local factors, as shown in **Fig. 10**.

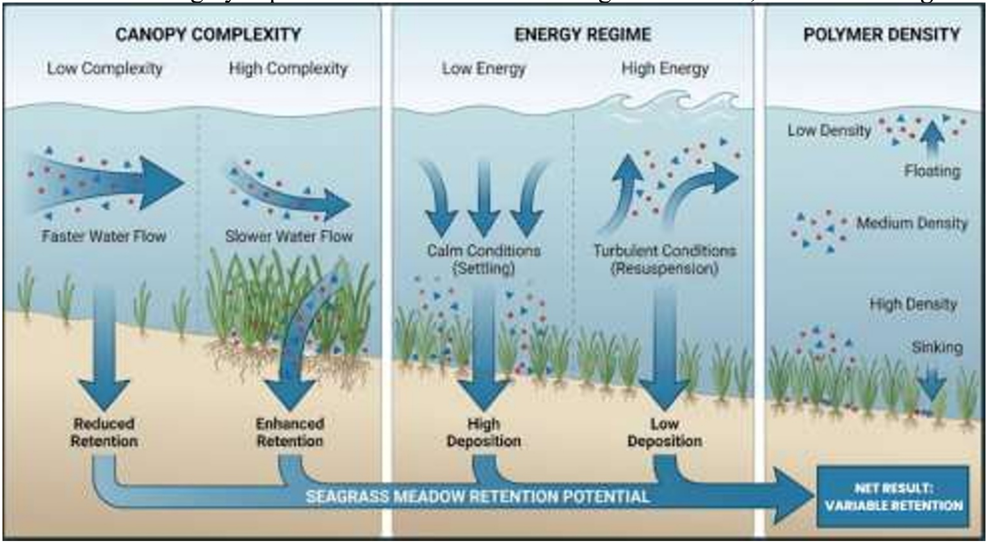

Fig. 10. Biophysical controls on microplastic retention in seagrass meadows.

The specific morphology and life history of seagrass species are paramount; for instance, small, ephemeral species with low canopy complexity, such as *Halophila ovalis*, have been shown to be ineffective at trapping MPs compared to larger, more structurally complex species [28]. Similarly, the density of the seagrass canopy is a critical variable, with denser meadows exhibiting a greater potential to attenuate flow and trap particles. Other influential factors include the local hydrodynamic regime (e.g., high-energy vs. low-energy environments), tidal position of the meadow (intertidal vs. subtidal), and characteristics of the plastic particles themselves, such as size, shape, and density. Therefore, the scientific question has matured from a simple binary of whether seagrasses are sinks to a more sophisticated inquiry into the specific biophysical conditions under which they function as effective traps for microplastic pollution.

3.7.3 Ingestion and bioaccumulation by seagrass-associated fauna

Seagrass meadows are highly efficient at accumulating microplastics (MPs), transforming them from a potential repository into a critical source for trophic transfer, thereby increasing the bioavailability of MPs to the diverse organisms that inhabit these ecosystems. Ingestion of MPs has been documented across various feeding guilds and trophic levels within the seagrass food web, serving as a primary pathway for contamination to spread throughout the ecosystem. Organisms that feed on or within the sediment, such as sea cucumbers and sea urchins, are directly exposed to high concentrations of accumulated MPs and consume them along with sediment and detritus [29,30]. Bivalves such as the commercially important clam, along with benthic filter feeders, accumulate MPs by filtering contaminated water that flows through the meadow [20,31]. Herbivores and detritivores, such as crabs, ingest MPs that have adhered to seagrass blades or their detritus, representing a significant and viable pathway for MPs to enter benthic marine food webs [32]. Higher-trophic-level organisms, including various fish species, also ingest MPs either directly by consuming particles mistaken for prey or indirectly through the consumption of contaminated prey items [33,34]. The probability of ingestion often depends on the specific feeding preferences of the fish and the relative availability of natural prey versus MPs. Widespread ingestion throughout the food web is a significant concern. It not only poses a direct physical and toxicological threat to the organisms themselves but also raises serious questions about human health risks associated with the consumption of contaminated seafood harvested from these productive ecosystems.

The threat posed by microplastics extends beyond their mere physical presence. Microplastics serve as effective vectors for transporting harmful chemical contaminants because of their chemical composition and large surface area-to-volume ratio. These chemicals can be classified into two main categories: intrinsic additives incorporated during manufacturing, and extrinsic pollutants adsorbed from the surrounding environment. Intrinsic additives, such as plasticizers (e.g., phthalate acid esters [PAEs] and organophosphate esters [OPEs]), flame retardants, and UV stabilizers, have the potential to leach out of the plastic matrix over time. Studies have detected significant concentrations of various plasticizers in seagrass tissues (*Posidonia oceanica*), associated sediments, and resident biota, including mussels and fish, thereby confirming their bioaccumulation within the food chain [35]. For instance, the concentrations of certain PAEs and their non-phthalate alternatives in *Posidonia oceanica* have been measured at levels up to 908 ng/g^{-1} and 151 $ng\ g^{-1}$ dry weight, respectively. The desorption of these and other sorbed pollutants, such as persistent organic pollutants (POPs), within the seagrass ecosystem can lead to chronic toxicological effects on both flora and fauna, thereby adding a chemical dimension to the physical threat of microplastic pollution. **Fig. 11** illustrates the two distinct pathways of chemical exposure identified in seagrass ecosystems.

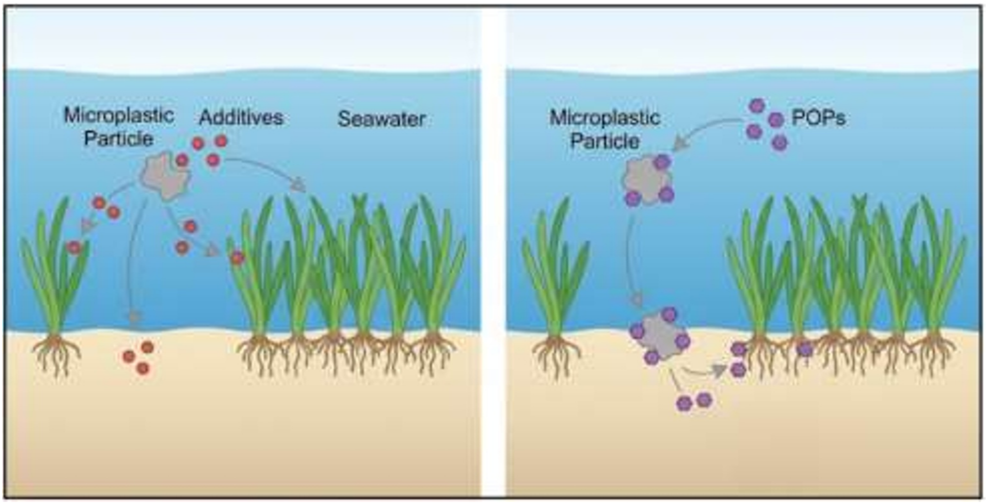

Fig. 11. Conceptual model of MPs as chemical vectors in seagrass food webs.

3.7.4 The influence of microplastics on seagrass and associated organisms

The accumulation of microplastics within seagrass meadows poses a direct and multifaceted threat to the health of seagrasses and the diverse communities they support. These impacts can be broadly categorized as direct physiological effects on plants, sub-lethal stressors arising from chemical alterations, and indirect effects that cascade through the ecosystem. Experimental studies have provided compelling evidence that micro- and nanoplastics can directly harm seagrass physiology and morphology [36]. In mesocosm experiments using the Mediterranean species *Cymodocea nodosa*, exposure to polystyrene MPs and nanoplastics (NPs) resulted in severe physiological consequences. Notably, the exposure led to complete degeneration of adventitious roots, which are crucial for nutrient uptake and anchorage. This was accompanied by a significant reduction in the number of leaves per shoot, and the rate of leaf loss surpassed the rate of new leaf production, indicating a net decline in plant biomass. MPs were found to reduce the photochemical efficiency of photosynthesis, a key indicator of plant stress. The physical presence of plastic particles was the primary driver of these impacts. Both macro- and microplastics can adhere to leaf surfaces, a process that physically blocks light and inhibits gas exchange, thereby directly interfering with the fundamental processes of photosynthesis and respiration. At a larger scale, macroplastics, such as discarded bags or sheeting, can smother patches of seagrass, creating anoxic conditions in the sediment below and physically preventing rhizome growth and the emergence of new shoots. However, the response to MP exposure was not uniform across all conditions. One study on *Zostera marina* found that short-term exposure did not significantly affect bicarbonate utilization or photosynthetic efficiency, suggesting that the severity of the impacts may be species-specific, dependent on the duration and concentration of exposure, or related to the type of polymer [37].

In addition to direct physical interference, plastics introduce chemical stressors into the seagrass environment. Leaching of chemical additives from the plastic matrix can induce sublethal physiological stress. For example, exposure to Bisphenol A (BPA), a common plastic component, has been shown to reduce chlorophyll content and cause a significant accumulation of peroxide in the tissues of *Cymodocea nodosa*, a biochemical marker of oxidative stress[38]. Nanoplastics appear to be particularly potent in this regard: shoots exposed to NPs exhibited greater oxidative damage and higher phenol content a plant defense response than those exposed to MPs or control conditions [38]. This suggests that smaller NPs may facilitate their uptake into plant tissues, leading to more severe internal cellular damage. The accumulation of plastics, including those marketed as "biodegradable, " can profoundly alter the biogeochemistry of sediment, which is critical for seagrass health. Studies have demonstrated that the burial of plastic bags on the seafloor leads to a reduction in sediment pore-water oxygen concentration and a decrease in pH[38]. The creation of anoxic microzones can disrupt essential microbial processes, such as nutrient cycling and organic matter decomposition, and may directly inhibit the ability of seagrass roots to absorb nutrients[38]. These geochemical shifts can have cascading ecological consequences, altering competitive interactions between seagrass species and promoting changes in clonal growth forms, potentially leading to spatial segregation and shifts in community structure [38].

The impacts of microplastics extend beyond seagrass plants to the complex web of life they support. Epiphytic communities, which play crucial roles in the productivity and trophic dynamics of meadows, are also at risk. MPs may cause physical harm to delicate epiphytic organisms through impalement or abrasion, and can increase the local concentration of leached toxins, potentially disrupting their metabolic processes and altering community composition [25,37]. Because many grazers selectively feed on these epiphytic layers, any disruption could have significant bottom-up effects on the food web. There is also emerging evidence of community-level effects on benthic macrofauna. A study on *Posidonia oceanica* meadows found that both the abundance and species richness of macrofauna associated with seagrass rhizomes were negatively correlated with the abundance of microplastics in the sediment [39]. This indicates that high concentrations of MPs can degrade the habitat quality of these organisms, leading to a decline in benthic biodiversity. This effect goes beyond the direct harm of ingestion and points to the broader ecosystem-level consequences of sediment contamination.

3.8 Research gaps in seagrass-microplastic interactions

Despite the rapid acceleration of research, the field of seagrass-microplastic interactions is still in its infancy. The existing body of literature, while foundational, is punctuated by significant knowledge gaps that currently limit a comprehensive understanding of risks and hinder the development of effective management strategies. These gaps, frequently highlighted by researchers, span the methodological, geographical, and thematic domains. One of the most critical and frequently cited barriers to progress in this field is the lack of standardized methodologies. Studies have employed a wide variety of techniques for sampling (e.g., different corer sizes and sampling depths), extraction (e.g., diverse density separation fluids, digestion protocols), and identification of microplastics. Furthermore, data are often reported in inconsistent units (e.g., items per kg of dry sediment, items per square meter, and items per blade), making direct comparisons between studies exceptionally difficult, if not impossible. This methodological heterogeneity severely hinders the ability to conduct robust meta-analyses, synthesize data on a global scale, and establish reliable baselines for long-term monitoring. Establishing internationally agreed-upon protocols for sampling, processing, and reporting MP data in seagrass ecosystems is arguably the most urgent priority of the research community.

Although the presence of MPs in seagrass beds is well documented, evidence linking this contamination to tangible, long-term impacts on seagrass health and ecosystem function remains weak and inconclusive. There is a pressing need for more research focused on the direct effects of chronic low-level MP exposure on critical physiological processes, such as growth, development, and primary productivity. A major frontier for future research lies in quantifying the impact of MPs on biogeochemical cycles in seagrass sediments. It is largely unknown how MPs alter microbial community function, organic matter decomposition, nutrient cycling, and most importantly, the net carbon sequestration and storage capacity of these vital blue carbon ecosystems. Answering these questions is essential to determine whether plastic pollution poses a significant threat to climate mitigation services provided by seagrasses. Furthermore, although numerous studies have documented the ingestion of MPs by seagrass-associated fauna, our understanding of the broader implications of the food web is still rudimentary. The precise dynamics of trophic transfer, including the potential for the biomagnification of plastics or their associated chemical contaminants in the food chain, are poorly understood. The cumulative and synergistic effects of the physical presence of plastics, combined with the toxicological impacts of leached additives on organisms at different trophic levels, remain a critical area for investigation. Further research is required to move beyond simple documentation of ingestion to a more mechanistic understanding of the ecological consequences for population health, community structure, and overall stability of the seagrass food web.

The current body of research is overwhelmingly focused on microplastics, leaving significant knowledge gaps regarding other components of the plastic pollution problem. The impacts of macroplastics are often under-reported, and there is a near-total absence of research on nanoplastics in seagrass ecosystems, despite theoretical and experimental evidence suggesting they may pose a greater toxicological risk due to their ability to cross biological membranes. Similarly, the long-term fate and ecological impacts of so-called "biodegradable" plastics in anoxic seagrass sediments are largely unknown. Geographically, the research is heavily biased towards a few key regions, primarily China, the Mediterranean, and parts of Southeast Asia. This leaves vast areas with extensive seagrass meadows, such as those in Australia, the Americas, and Africa, as virtual data deserts.1 This geographical disparity prevents truly global assessment of the problem. Furthermore, research has focused on a very limited number of seagrass species, noting that less than 15% of the world's known seagrass species have been investigated for MP contamination, limiting the generalizability of the current findings.

A comprehensive understanding of the sources and transport pathways of MPs in seagrass meadows is lacking. While proximity to urban centers, rivers, and aquaculture sites is often implicated, few studies have conducted rigorous source apportionment analyses to link the specific types, shapes, and polymer compositions of MPs found in meadows to specific land- or marine-based activities. Developing and applying models that integrate local hydrodynamics with pollution source data is a critical next step in predicting which seagrass meadows are most at risk and in designing effective, targeted mitigation strategies.

4 Conclusion

This review confirms that seagrass meadows function as critical accumulation zones for microplastic pollution, driven by the synergistic interaction between physical canopy attenuation and biological adhesion mechanisms. While this sequestration effectively filters the water column, it simultaneously creates an "ecological trap" where accumulated plastics and their associated chemical contaminants increase bioavailability to benthic fauna and induce physiological stress in the seagrasses themselves. Despite the rapidly expanding literature, the current body of evidence is fragmented by the significant methodological inconsistencies and geographical biases that limit global comparability. Consequently, future research must urgently prioritize four key areas to advance the field: standardization of sampling protocols, expansion of study sites to underrepresented regions, investigation of microplastic impacts on long-term blue carbon functions, and exploration of the largely unknown threat posed by nanoplastics.

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