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REVIEW ARTICLE

PLASTIC POLLUTION AS A DRIVER OF SEAGRASS ECOSYSTEM DEGRADATION: A SYSTEMATIC REVIEW OF IMPACTS AND MITIGATION APPROACHES

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ABSTRACT

Seagrass ecosystems are essential coastal habitats that contribute significantly to biodiversity conservation, carbon sequestration, and the stability of marine food webs. However, they are increasingly threatened by plastic pollution, a growing global concern with far-reaching ecological implications. This systematic review analyzed 113 peer-reviewed articles published between 2010 and 2025 using PRISMA guidelines, revealing a growing body of literature addressing this issue. The most reported forms of plastic were fragments (34.49%), fibers (24.14%), and sticks (17.24%), commonly originating from fishing gear, textiles, and packaging debris. In terms of size, microplastics (<5 mm) accounted for 44.90%, followed by macroplastics (>25 mm, 34.69%) and mesoplastics (5–25 mm, 20.41%). Plastic interactions were most frequently observed on seagrass leaves (40.82%) and associated fauna (28.57%), affecting photosynthesis, respiration, and trophic dynamics. The review also highlights significant knowledge gaps—particularly in the tropics and underrepresented regions—and the urgent need for standardized methodologies and long-term ecological monitoring. A framework for mitigation is proposed, integrating source reduction, policy enforcement, ecosystem restoration, and community engagement as key components. This review underscores that addressing plastic pollution in seagrass ecosystems is not only vital for ecological resilience but also critical to climate action and sustainable coastal development. Future research must prioritize interdisciplinary approaches and scalable solutions to ensure the protection of these vital blue carbon ecosystems in an era of rapid environmental change.

KEYWORDS

Seagrass ecosystems; Plastic pollution; Blue Carbon; Ecosystem threats; Mitigation strategies

1. INTRODUCTION

Seagrass meadows are vital marine ecosystems that play a significant role in maintaining coastal biodiversity and providing essential ecological services (Atmaja et al., 2021). Found in shallow coastal waters, these underwater flowering plants contribute to carbon sequestration, sediment stabilization, and nutrient cycling, making them important blue carbon ecosystems (Gil et al., 2006; Orbita and Mukai, 2013; Huxham et al., 2018). Seagrasses act as nurseries for various marine species, offering habitat and food for fish, crustaceans, and other invertebrates (Atmaja et al., 2024; Dalia Susan et al., 2014; Heck et al., 2003). Additionally, they enhance water quality by trapping suspended particles and reducing coastal erosion through their complex root systems. The loss of seagrass meadows could significantly disrupt coastal food webs and compromise the livelihoods of communities that depend on fisheries and tourism.

In recent years, seagrass meadows have increasingly become sinks for plastic pollution, which poses a serious threat to their health and functionality (de los Santos et al., 2021; Fong et al., 2023). Studies have revealed the widespread presence of both macroplastics and microplastics entangled in seagrass blades or buried within the sediment beneath these meadows (Cozzolino et al., 2020b; Dahl et al., 2021; Seng et al., 2020). Microplastics, in particular, have been detected in alarming concentrations, adhering to leaves and being ingested by organisms that rely on seagrass habitats (Naidoo and Glassom, 2019; Nugraha et al., 2025). The accumulation of plastics can obstruct light penetration and hinder photosynthesis, leading to reduced growth rates and compromised carbon sequestration capabilities (Kumala et al., 2024). Furthermore, toxic substances associated with plastics, such as heavy metals and persistent organic pollutants, can exacerbate stress on seagrass and associated fauna, intensifying the degradation of these ecosystems (Adi et al., 2024; Thuan et al., 2024).

The primary sources of plastic pollution in seagrass meadows include riverine inputs, coastal urban runoff, and maritime activities (Arifin et al., 2023). Rivers act as significant conduits, transporting land-based plastic waste directly into coastal waters, where it settles among seagrass beds. Coastal tourism, recreational activities, and aquaculture also contribute to the influx of plastics, particularly in regions lacking effective waste management practices (Suteja et al., 2025). Additionally, fishing gear and plastic debris from shipping lanes are prevalent sources, introducing both macroplastics and microplastics into seagrass ecosystems (Daniel et al., 2020). The fragmentation of larger plastic items further perpetuates microplastic contamination, posing chronic risks to seagrass and the broader marine food web.

Despite the increasing recognition of plastic pollution in seagrass habitats, comprehensive assessments of its sources, impacts, and management remain limited. A systematic review of existing literature is urgently needed to synthesize current knowledge and identify gaps in research. Understanding the extent and implications of plastic contamination is critical for informing conservation strategies and policy interventions aimed at protecting seagrass ecosystems. Furthermore, given the role of seagrass meadows in carbon sequestration and climate regulation,

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addressing plastic pollution is essential for achieving broader environmental sustainability goals. This review aims to consolidate findings on the impact of plastic pollution on seagrass, highlight emerging threats, and propose future research directions to mitigate these impacts effectively.

2. Materials And Methods

2.1 Search Strategy

This systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and methodological rigor (Mishra and Mishra, 2023).

A comprehensive literature search was performed across the following scientific databases: Scopus, Web of Science, ScienceDirect, Google Scholar, and PubMed. The search was conducted using the following keywords: (Seagrass AND (plastic OR microplastic) AND (pollution OR contamination) AND (impact OR effect)). The search was limited to peer-reviewed articles published in English between 2010 and 2025 to ensure the inclusion of the most relevant and recent studies.

A PRISMA flow diagram was created to visually summarize the study selection process. This diagram shows the number of studies identified, screened, assessed for eligibility, and included in the final review, offering a clear representation of the review's methodology (Figure 1).

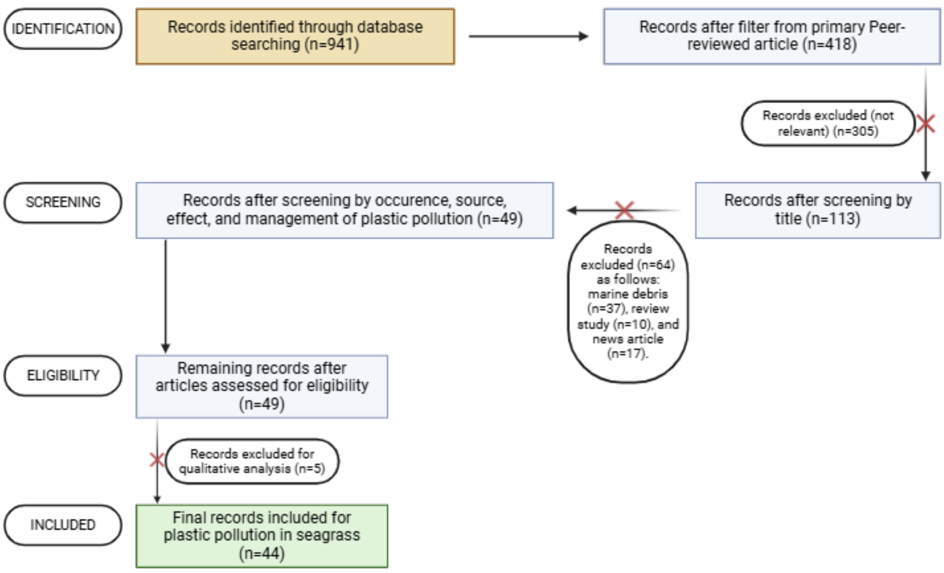

Figure 1: Flowchart of systematic review process adapted from the PRISMA guidelines.

2.2 Inclusion and Exclusion Criteria

Articles were included in the review if they met specific criteria: first, the study needed to focus on plastic pollution in seagrass ecosystems, addressing any of the following aspects: occurrence, sources, effects, or management. Only peer-reviewed original research studies were included, such as experimental, observational, and field-based studies. Additionally, only studies published in English between 2010 and 2025 were considered. Studies were excluded if they did not address seagrass ecosystems specifically, or if they were grey literature (e.g., reports, books, and non-peer-reviewed articles). Studies lacking original data or those not directly investigating the impacts of plastic pollution on seagrass meadows were also excluded.

The initial search identified 941 articles. These were screened for relevance first by title and abstract, followed by a full-text review. In total, 113 studies were ultimately included in the final analysis.

2.3 Data Extraction And Synthesis

Data from the selected studies were extracted using a standardized extraction table. This table included the following key categories: authors and year of publication, study area, type of plastic pollution (e.g., microplastics, macroplastics, fibers, fragments), environmental impacts (e.g., effects on photosynthesis, respiration, and trophic dynamics), mitigation strategies (e.g., waste management, policy enforcement), and methodology used (e.g., field-based, laboratory-based, surveys).

The extracted data were analyzed through thematic analysis to categorize and synthesize findings. The studies were grouped into categories based on the types of plastics reported (macroplastics, microplastics, fibers, etc.), the ecological impacts (such as effects on seagrass growth, light penetration, and fauna interactions), and the mitigation strategies discussed (e.g., restoration efforts, policy enforcement). This thematic analysis allowed for the identification of patterns and gaps in the existing research. To ensure consistency and reliability in the data extraction and synthesis process, two independent reviewers conducted the analysis. Any disagreements between the reviewers were resolved through discussion and consensus.

2.4 Study Quality Assessment

The quality of the included studies was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Tool. This tool evaluates methodological quality by considering factors such as the study design (e.g., experimental, observational), data collection methods (e.g., sample size, methodology rigor), potential risks of bias (e.g., selection or reporting bias), and the robustness of statistical analysis (if applicable) (Munn et al., 2019; Porritt et al., 2014). Each study was rated as high, medium, or low quality based on these criteria. Studies rated as low quality were excluded from the final synthesis to ensure the reliability and credibility of the review's findings.

2.5 Potential Biases

While every effort was made to ensure comprehensive inclusion, certain biases may have influenced the review. Language bias is one such limitation, as only studies published in English were included, which may have excluded relevant studies published in other languages. Additionally, there is a potential publication bias, where studies with positive or significant findings may be more likely to be published, thus over-representing studies with such results. These potential biases were taken into account when interpreting the review's findings, and their impact was minimized by following a transparent and systematic approach throughout the review process.

3. Result And Discussion

3.1 Overview of PRISMA Screening Result

As part of the systematic review on plastic pollution in seagrass ecosystems, number of research articles accessed from various scientific databases (Figure 2). ScienceDirect emerged as the most utilized source, contributing 47 papers, reflecting its broad coverage of marine pollution, ecology, and environmental science literature. Springer followed with 27 articles, offering substantial content related to ecological dynamics and seagrass-specific studies. Frontiers provided 17 papers, many of which emphasized experimental approaches and open-access contributions. MDPI contributed 12 studies, particularly on recent trends in microplastic contamination and methodological developments. Lastly, other sources, including grey literature and institutional databases, added 10 papers to the review.

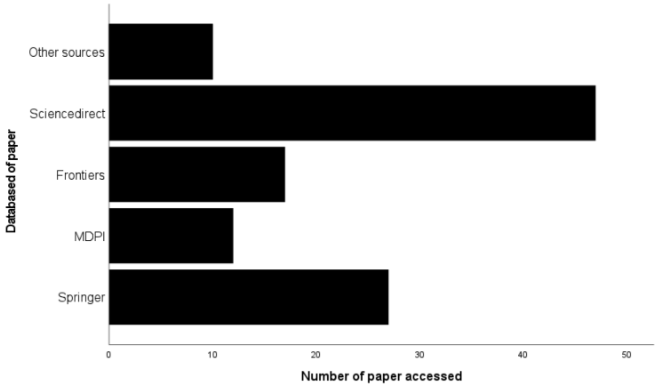

Figure 2: Number of Articles Retrieved per Database on Plastic Pollution in Seagrass Ecosystems

The composition of plastic pollution identified specifically within seagrass displays considerable variation in form, each with distinct implications for ecological impact (Figure 3). The data reveal that plastic fragments are the most frequently reported form, comprising 34.49% of occurrences. These fragments often result from the degradation of larger debris and are commonly found embedded in sediments or trapped among seagrass structures, potentially disrupting plant growth and sediment processes. Fibers follow at 24.14%, typically originating from fishing gear and synthetic textiles. Their fine, filamentous nature enables them to become easily entangled in seagrass leaves or ingested by associated fauna, posing risks of trophic transfer and internal blockages. Sticks, at 17.24%, likely represent broken or discarded rigid plastics, such as aquaculture equipment or packaging remnants, which may mechanically damage seagrass blades or embed in the substrate. Plastic films (12.07%) are often associated with single-use items and pose a threat by covering leaf surfaces, thereby reducing light penetration and gas exchange. Foams (8.62%) and pellets (3.45%) appear less frequently but are of concern due to their buoyancy, persistence, and potential for ingestion by benthic and pelagic species.

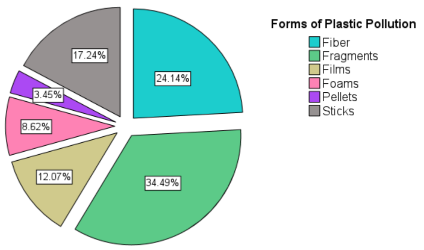

Figure 3: Composition of Different Forms of Plastic Pollution in Seagrass Ecosystems

In addition to variations in plastic form, the proportions of plastic pollution by size category within seagrass ecosystems also exhibit notable differences (Figure 4). Based on a synthesis of literature data, microplastics (<5 mm) are the most commonly reported, representing 44.90% of all observations. Due to their small size and widespread dispersion, microplastics can infiltrate sediment layers, adhere to seagrass surfaces, and be ingested by associated fauna, potentially leading to bioaccumulation and long-term ecological effects. Macroplastics (>25 mm) account for 34.69% of the reported pollution. These larger items can cause physical damage to seagrass structures and contribute to habitat alteration. Meanwhile, mesoplastics (5–25 mm) comprise 20.41% and represent an intermediate category that poses dual risks—their size allows for both entanglement in plant structures and ingestion by marine organisms.

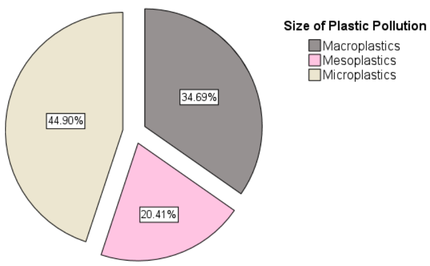

Figure 4: Proportional Distribution of Plastic Pollution by Size Class in Seagrass Ecosystems

3.2 Pathways of Plastic Retention in Seagrass Ecosystems

The distribution of plastic pollution within seagrass ecosystems demonstrates a clear pattern of accumulation across various structural components of the plant and its associated fauna (Figure 5). The leaves are the most affected part, accounting for 40.82% of all recorded plastic interactions. The associated fauna—organisms that live within or depend on seagrass habitats—constitute the second-largest category, with 28.57%, through ingestion or entrapment, which can lead to trophic transfer of plastics and ecosystem-level consequences. Although less affected in relative terms, the stems (6.12%) and roots (4.08%) are still important points of interaction, as plastic accumulation in these areas may interfere with plant stability, anchorage, and nutrient uptake. Collectively, this distribution illustrates the multifaceted threat plastic pollution poses—not only to the structural and functional integrity of seagrass plants but also to the broader ecological network they support.

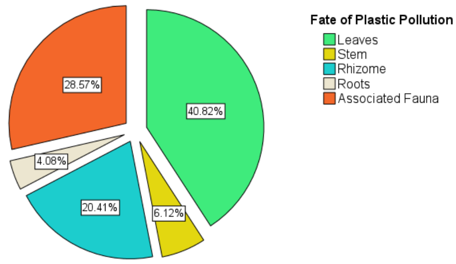

Figure 5: Fate of Plastic Debris Across Seagrass Structures and Associated Fauna

4. Discussion

4.1 Global concern of Plastics Pollution in Seagrass Ecosystem

Plastics pollution has emerged as a critical global environmental issue, with increasing evidence of its detrimental impacts on seagrass ecosystems. The global concern surrounding plastic pollution in seagrass ecosystems is reflected not only in its widespread ecological impacts but also in the breadth of scientific research dedicated to this issue. Seagrasses are key coastal habitats that deliver vital ecosystem services, including carbon sequestration, shoreline protection, and serving as nursery grounds for marine species. However, both macroplastics and microplastics threaten these ecosystems through physical smothering, reduced light availability, chemical contamination, and altered sediment characteristics (Greenshields et al., 2025; Kaldy et al., 2025; Cozzolino et al., 2020b; Molin et al., 2023). This urgency is underscored by the systematic review's findings on research distribution, where the result depicting the number of articles retrieved per database reveals a robust and growing body of literature addressing plastic pollution in seagrass habitats. ScienceDirect, for instance, contributes the largest share of articles, illustrating its comprehensive coverage of marine pollution and ecological studies. Other major databases like Springer, Frontiers, and MDPI also provide substantial research outputs, emphasizing experimental approaches and emerging trends such as microplastic contamination. The concentration of studies in these databases indicates a broad scientific engagement with the topic, reflecting its global relevance and the multidisciplinary efforts required to understand and mitigate plastic pollution's effects on seagrass ecosystems worldwide.

Regionally, plastic pollution manifests differently depending on local environmental and socio-economic factors. In the Temperate North Atlantic, densely populated coastlines and industrialized economies contribute significantly to plastic discharge, particularly from urban runoff and maritime activities (Garrard et al., 2024). This has direct implications for seagrass meadows located in areas such as the North Sea and the eastern U.S. coastline, where microplastic accumulation in sediments is becoming increasingly common. Such accumulation can disrupt plant physiological functions and adversely affect benthic communities associated with these habitats. Supporting this, field studies conducted in Old Dorney Harbour (Scotland) and Griend Island (Netherlands), have provided clear evidence of macroplastic pollution stemming from marine aquaculture activities (Skirtun et al., 2022). These plastics not only threaten marine organisms through entanglement and ingestion, but also introduce toxic chemical additives into the ecosystem (Pan et al., 2025; Thuan et al., 2024; de Barros et al., 2020). Furthermore, floating or submerged debris can act as vectors for non-native species, facilitating biological invasions, and may create unnatural substrates on the seafloor that altered native habitat structures. Collectively, these findings highlight the multifaceted ways in which plastic pollution can compromise the ecological integrity of seagrass ecosystems in this region.

Similarly, The Tropical Indo-Pacific, encompassing Southeast Asia and the Coral Triangle, is a global hotspot for plastic pollution (Nakayama and Osako, 2024) due to high population growth, rapid urbanization, and inadequate waste treatment (Frigo et al., 2025; Goh et al., 2025). This region contains some of the world's most extensive and biodiverse seagrass meadows (Short et al., 2007), which are under immediate threat from plastic entanglement, sediment contamination, and ingestion by associated fauna (Short et al., 2011; Waycott et al., 2009). Evidence from Southeast Asian countries such as Indonesia, Malaysia, Thailand, the Philippines, and Vietnam reveals that plastic ingestion by marine species associated with seagrass ecosystems predominantly involves Teleostei fish, accounting for 40% (Budihardjo et al., 2025). However, significant knowledge gaps persist concerning other important groups, including seabirds, sea snakes, and commercially valuable fish species, highlighting the urgent need for broader research into the varied impacts of plastic pollution within this ecologically critical region.

Despite the growing body of literature on plastic pollution in seagrass ecosystems, there are notable regional differences in the focus of research. In temperate regions, research tends to focus on macroplastics and their immediate physical impacts on seagrass, while tropical regions emphasize the long-term ecological risks posed by microplastics. This disparity may be attributed to differences in local pollution sources, waste management practices, and the urgency with which the issue is addressed. For instance, regions with advanced waste management systems, such as parts of Europe, exhibit relatively lower concentrations of plastics in seagrass meadows compared to regions where waste management infrastructure is inadequate, such as in parts of Southeast Asia.

The disparity in research focus also highlights the significant gaps in understanding the full scope of plastic pollution's impact on seagrass ecosystems, particularly in the tropics. While the presence of microplastics in these ecosystems is well-documented, studies on the chemical contaminants associated with plastics, such as phthalates and heavy metals, remain sparse. These chemicals can leach from plastics and exacerbate the harmful effects of plastic pollution, leading to chronic stress on both seagrass and the organisms that depend on it. Given the high biodiversity and carbon sequestration potential of tropical seagrass meadows, addressing these knowledge gaps is essential for the effective protection and restoration of these vital ecosystems.

Given the ecological significance of seagrass ecosystems across bioregions, plastic pollution presents a universal yet regionally nuanced threat. Addressing these challenges requires a combination of global policy initiatives and localized management strategies tailored to each bioregion's environmental, socio-economic, and governance contexts. Prioritizing research in underrepresented regions and strengthening transboundary cooperation will be essential to mitigate plastic impacts and protect these critical blue carbon ecosystems.

4.2 Characteristics of Plastics Pollution and Interaction with Seagrass Ecosystems

Plastic pollution in seagrass ecosystems presents a complex and multifaceted threat, characterized by diverse forms that vary in size, composition, and behaviour in the marine environment. To illustrate the pathways through which plastic pollution impacts seagrass ecosystems, we present a conceptual diagram (Figure 6) that outlines the entry points, interactions, and ecological consequences of plastic pollution.

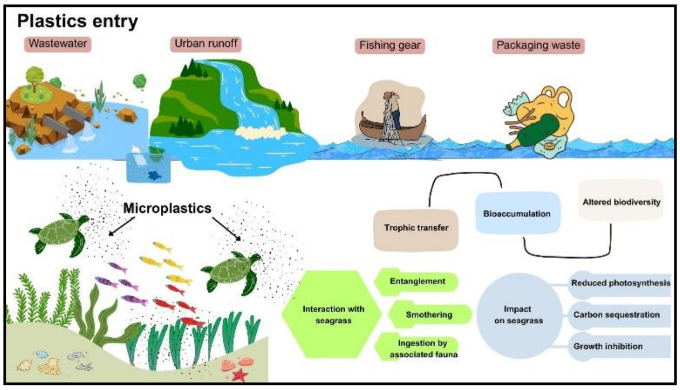

Figure 6: Sources and ecological impacts of plastic pollution on seagrass habitats, including microplastic interactions and effects such as bioaccumulation and reduced ecosystem functions.

In addition to the spatial distribution of plastics within seagrass habitats, the size composition of plastic pollution further illustrates the diverse threats these ecosystems face (Figure 4).

Microplastics, defined as particles smaller than 5 mm, dominate the pollution profile, constituting 44.90% of observations. Their small size facilitates infiltration into sediments and adherence to seagrass blades, enabling ingestion by a wide range of benthic and pelagic organisms (de Barros et al., 2020; McGoran et al., 2020). Consequently, microplastics may exert chronic and cumulative effects on ecosystem health. Conversely, macroplastics—those exceeding 25 mm—make up 34.69% of the pollution and contribute primarily through mechanical damage to seagrass structures and alteration of sediment dynamics (Greenshields et al., 2025). Between these extremes, mesoplastics (5–25 mm), which account for 20.41%, present dual risks; their size enables both entanglement in plant tissues and ingestion by marine fauna, thereby compounding their ecological impact.

Furthermore, the form of plastic pollution within seagrass ecosystems reveals considerable variation (Figure 3), each type with distinct ecological implications. Plastic fragments are the most prevalent, representing 34.49% of the debris, and typically originate from the breakdown of larger items (Di Giulio et al., 2024; Liro et al., 2023). These fragments often embed within sediments or become trapped in seagrass canopies, thereby disrupting seagrass growth and sediment processes. Plastic fibers, comprising 24.14% of pollution, predominantly derive from fishing gear and synthetic textiles, and their filamentous nature makes them particularly prone to entanglement in seagrass leaves or ingestion by associated fauna (Daniel et al., 2020; Gilman et al., 2021). This dual threat increases the likelihood of trophic transfer and physical harm. Additionally, rigid plastics such as sticks, which constitute 17.24%, may physically damage seagrass blades or disturb sediment substrates, negatively affecting plant stability and nutrient uptake. While less abundant, plastic films (12.07%), foams (8.62%), and pellets (3.45%) also contribute to ecosystem stress.

More importantly, these plastics interact differently with seagrass habitats, often depending on both the form of plastic and the structural characteristics of the seagrass species involved. Notably, seagrass leaves bear the brunt of plastic accumulation (Figure 5), accounting for 40.82% of all recorded plastic interactions. This predominance is significant because plastic debris entangled in or settled upon seagrass leaves can obstruct light penetration, thereby impairing photosynthesis, reducing respiration, and ultimately decreasing the overall productivity and carbon sequestration potential of seagrass meadows (Adyel and Macreadie, 2022; Hou et al., 2024; Menicagli et al., 2022; Molin et al., 2023; Nugraha et al., 2025; Cozzolino et al., 2020a). Moreover, plastic contamination extends beyond plant structures to the associated fauna, which constitute 28.57% (Figure 5) of interactions through ingestion or entrapment. Such ingestion poses critical risks, including physical blockages and exposure to toxic chemicals that can bioaccumulate, thus raising concerns about the transfer of plastics through marine food webs (Ajith et al., 2020; Alfaro-Núñez et al., 2021). Crucially, as an evidence to this, study revealed that the abundance and diversity of macrofauna associated with Posidonia oceanica rhizomes were found to decline in response to increased microplastic concentrations, indicating that plastics pose significant ecological risks not only to the seagrass itself but also to the complex benthic communities it supports (Martinez et al., 2024). Additionally, the study in Thalassia testudinum highlights that grazers preferentially consume seagrass blades with higher epibiont densities, suggesting that microplastic accumulation may occur through entrapment by epibionts or biofilm attachment. This finding marks the first documented presence of microplastics on marine vascular plants and proposes macroherbivory as a potential pathway for microplastic transfer into marine food webs, emphasizing the pervasive reach of plastic pollution in coastal ecosystems (Goss et al., 2018).These findings reinforce the broader result that plastic pollution in seagrass ecosystems adversely affects associated fauna, impairing biodiversity and ecosystem function, and underscore the urgent need to address plastic contamination to preserve these critical coastal habitats.

When considering plastic size, microplastics (<5 mm) emerge as the most commonly reported, accounting for nearly half of the plastic pollution observed in seagrass meadows. Their small size allows them to infiltrate sediment layers, adhere to seagrass surfaces, and be ingested by a wide array of marine organisms, raising concerns about the bioaccumulation of plastic-associated chemicals such as heavy metals and persistent organic pollutants. While some studies argue that microplastics may have minimal direct effects on seagrass growth, others suggest even small concentrations of these plastics can significantly impair photosynthetic activity and reduce overall plant productivity. The lack of consensus in these findings could be attributed to variations in study methodologies, such as the type of seagrass species studied, exposure duration, and plastic concentrations. In contrast, macroplastics (>25 mm), though less abundant, present more immediate and visible threats to seagrass ecosystems. These larger plastics, such as discarded fishing nets and packaging debris, physically damage seagrass blades, disrupt sediment dynamics, and obstruct light, all of which directly affect seagrass health and functionality. However, despite their more obvious impacts, macroplastics tend to be more localized, and their occurrence is typically associated with areas of high human activity, such as shipping lanes and industrial coastal zones. The relative importance of macroplastics versus microplastics in seagrass ecosystems remains a point of debate, as some argue that macroplastics are easier to manage through cleanup efforts, while microplastics, due to their small size and widespread distribution, pose a far more persistent challenge.

Cross-study analysis reveals some contradictions regarding the ecological impacts of plastic pollution, particularly concerning microplastics and macroplastics. While most studies agree that macroplastics have immediate physical impacts, such as smothering seagrass and reducing light availability, there is less consensus on the long-term effects of microplastics, particularly their role in sediment disruption and their potential to act as vectors for toxic substances. In regions like the Mediterranean, where plastic pollution from shipping and fishing activities is widespread, macroplastics tend to be more prevalent, and their effects on seagrass ecosystems are well-documented. Conversely, in tropical regions like Southeast Asia, microplastics are more commonly found due to higher population densities, poor waste management practices, and intense coastal tourism. These regional differences highlight the need for context-specific research, as local pollution sources, environmental conditions, and waste management systems significantly influence the nature and impact of plastic pollution on seagrass meadows.

Despite the increasing body of research on plastic pollution in seagrass ecosystems, significant gaps remain in understanding the full scope of its ecological consequences. While the physical impacts of macroplastics are well-documented, less is known about the long-term effects of plastic-associated chemical contaminants on both seagrass and the organisms that depend on them. Chemical additives leached from plastics, such as phthalates, bisphenol A, and other persistent organic pollutants, could exacerbate the ecological harm caused by plastics, yet studies exploring these chemical interactions remain sparse. Furthermore, while much of the research on microplastics focuses on their prevalence and distribution, studies on their ecological effects, particularly in terms of long-term growth inhibition and sediment interaction, are still limited. Addressing these gaps will be crucial for developing comprehensive strategies to mitigate the effects of plastic pollution in seagrass ecosystems, particularly in regions that are currently underrepresented in the literature, such as the tropics.

Collectively, these findings underscore that plastic pollution in seagrass ecosystems is not merely a question of quantity but also of diverse forms and sizes, each interacting with seagrass habitats in unique and often deleterious ways. Thus, the interplay between plastic debris distribution, size, and composition elucidates the multifaceted nature of this environmental threat. Given the critical ecological functions of seagrass meadows, including carbon storage and habitat provision, it is imperative that future research and management efforts incorporate these complexities. Such an approach will enhance our ability to develop effective mitigation strategies aimed at preserving the health and resilience of these vital blue carbon ecosystems.

4.3 Mitigation Strategies and Conservation Approaches

Addressing plastic pollution in seagrass ecosystems requires a combination of preventive, remedial, and policy-driven actions (Figure 7). Central to these strategies is source reduction, which targets the prevention of plastic pollution at its origin. This involves improving coastal waste management, encouraging the use of biodegradable materials, and significantly reducing single-use plastics. By preventing plastics from entering the environment, this strategy plays a crucial role in protecting seagrass ecosystems from the outset (Arifin et al., 2023; Sheriff et al., 2025). In addition to source reduction, Best Management Practices (BMPs) are vital for controlling plastic waste and improving management practices in seagrass areas. This includes Extended Producer Responsibility (EPR), where producers are held accountable for the entire lifecycle of their products, as well as implementing plastic bans and taxes to reduce plastic use and waste (Harris et al., 2021). Supporting a circular economy also plays a role by encouraging the reuse and recycling of materials to minimize waste. Equally important are policy and regulation strategies, which strengthen the enforcement of plastic bans and taxes. Implementing strict regulations that support EPR initiatives ensures that plastic pollution is controlled at a systemic level, especially in coastal and marine environments where seagrass meadows are highly vulnerable.

Figure 7: Framework of Mitigation Strategies for Addressing Plastic Pollution in Seagrass Ecosystems and Pathways to Enhancing Ecosystem Health and Resilience

Moreover, efforts to restore and clean up polluted areas, including manual plastic removal, sediment remediation, and plastic capture barriers, help mitigate the effects of plastic that has already infiltrated seagrass meadows (Dokl et al., 2024). These restoration and cleanup actions provide immediate relief to ecosystems and enable the recovery of seagrass habitats. Research integration is essential—continued monitoring and species-specific risk assessments will refine mitigation and help prioritize actions

Lastly, conservation and community action are essential for the long-term protection of seagrass meadows. The establishment of Marine Protected Areas (MPAs) offers a sanctuary for seagrasses, while education and outreach programs raise awareness and foster stakeholder engagement to encourage sustainable practices (Rifai et al., 2024). Through these efforts, communities become active participants in safeguarding seagrass ecosystems, ensuring that conservation strategies are well-supported and effectively implemented.

By integrating these conservation strategies—spanning prevention, management, regulation, restoration, and community involvement—the health of seagrass ecosystems can be preserved, leading to improved biodiversity, enhanced ecosystem services, and a reduced plastic footprint in these vital coastal habitats. Together, these strategies form a holistic framework to safeguard seagrass ecosystems against escalating plastic pollution.

4.4 Future Research Directions

Future research on plastic pollution in seagrass ecosystems should focus on expanding the geographic and species coverage to fill existing gaps, particularly in underrepresented regions and lesser-studied seagrass species. Investigations are needed to better understand species-specific vulnerabilities and the differential impacts of various plastic types and sizes on seagrass physiology, growth, and ecosystem functions such as carbon sequestration. Long-term monitoring programs employing standardized methodologies would enhance the assessment of temporal trends and the effectiveness of mitigation efforts. Additionally, studies exploring the ecological consequences of plastic-associated chemical contaminants and microbe colonization on seagrass health and associated fauna are crucial. There is also a need for developing and testing innovative remediation techniques, including sediment remediation and plastic capture technologies, tailored to seagrass habitats. Furthermore, interdisciplinary research integrating social, economic, and policy dimensions can inform more effective management strategies by linking scientific findings to community engagement, policy frameworks, and sustainable coastal development. Finally, advancing predictive modeling of plastic pollution pathways and impacts under various climate change scenarios will support proactive conservation and restoration efforts, ensuring the resilience of these critical blue carbon ecosystems in the face of escalating environmental pressures.

5. Conclusion

The growing threat of plastic pollution in seagrass ecosystems, a critical habitat for coastal biodiversity and blue carbon storage has become a global concern. Synthesized evidence reveals that seagrass meadows are increasingly affected by macro- and microplastics, especially fragments and fibers, which accumulate on leaves and are ingested by associated fauna. These pollutants impair photosynthesis, reduce carbon sequestration, and threaten biodiversity. This review identifies key knowledge gaps, particularly in underrepresented regions and among lesser-studied species, underscoring the need for standardized research and long-term monitoring. A comprehensive mitigation framework—spanning source reduction, policy enforcement, habitat restoration, and community engagement—offers a viable path forward. Protecting seagrass ecosystems from plastic pollution is essential for maintaining ecological balance, strengthening climate resilience, and supporting sustainable coastal livelihoods. Continued research and coordinated action are imperative to preserve the resilience of these vital blue carbon ecosystems.

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