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REVIEW

Microplastics in Seagrass Ecosystems: A Review of Fate and Impacts

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ABSTRACT

Microplastics have been detected in seagrass ecosystems, raising concerns about their potential impacts on the ecological functions of seagrasses. Seagrass meadows are biodiversity hotspots as they provide habitats to diverse fish and invertebrates. They also play a crucial role in nutrient cycling, capturing carbon, and buffering coastal erosion. This review aims to present the fate of microplastics in seagrass ecosystems and their impacts on the ecosystems. A total of 66 scientific articles have been reviewed. The review highlights that seagrass meadows intercept microplastics, though the relevant results are currently inconclusive. Some microplastics attach to the epiphytes on seagrass blades or the seagrass blades while some accumulate in the seagrass sediment, causing enrichment of microplastics in seagrass meadows. Nonetheless, a few studies did not observe such intercepting effects. Microplastic enrichment, where observed, could be due to near-bed turbulent kinetic energy that entraps denser sinking microplastics. Microplastics can directly affect seagrasses by blocking light and nutrient transfer, affecting their shoot or leaf turnover, degenerating root and causing oxidative stress. However, a study on *Zostera marina* L. found that short-term exposure to microplastics did not significantly impact bicarbonate utilization and photosynthetic efficiency. Microplastic additives, particularly bisphenol A reduced chlorophyll and caused peroxide accumulation in *Cymodocea nodosa*. The presence of biodegradable plastics in the sediment might alter the distribution and interaction of seagrass species. Seagrasses could be affected indirectly through the potential impacts of microplastics on seagrass epiphytes but more studies are needed to confirm this. Desorption of pollutants sorbed on microplastics could negatively affect seagrass meadows. Further research could focus on the impacts of microplastic accumulation on the seagrass ecosystem and the processes therein, including nutrient cycling. Disintegration-oriented techniques and alternatives to conventional plastics are two strategies to mitigate microplastic prevalence in the environment.

Keywords: Ecosystems; Epiphytes; Interactions; Microplastics; Seagrass; Sediment

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1. Introduction

The presence of plastic waste in all parts of the environment has raised global concern. As of 2021, the global production of plastics stood at 400 million metric tons, and the number is expected to increase threefold by 2060. Increasing plastic production and consumption is frequently followed by a rising entry of plastic waste into the environment, often through the mismanagement of plastic waste. Approximately 30 million metric tons of plastics had found their way into the marine environments from 1970 to 2019 [1]. These plastics degrade in the environment over time into tiny particles called microplastics and nanoplastics. Microplastics derived from the breakdown of larger plastics discarded into the environment, such as water bottles, plastic bags, and other single-use plastics, are also called secondary microplastics. Plastic particles with sizes less than 5 mm are generally regarded as microplastics. Nanoplastics are fundamentally a subset of microplastics with extremely small sizes ranging from 1 to 1000 nm. Microplastics can also enter the marine environments directly from items containing them, such as cosmetics and paints. These primary microplastics further complicate marine plastic pollution [2].

Research on the prevalence of microplastics in ocean surface waters has found that the average concentration varies from 0.13 to 6.6 μg/L, with the highest recorded value being 670 μg/L in the North Pacific Ocean [3]. Forecasts suggest that the total quantity of microplastics could quadruple by 2060 [4]. The Mediterranean Sea, due to its semi-enclosed nature [5], is known as a significant hotspot for plastic waste, with average microplastic concentrations in seawater fluctuating between 1.4 and 7 μg/L [3]. Nevertheless, certain areas of the Mediterranean, such as France (56.9 μg/L) and a highly polluted hypersaline lagoon in Spain (9303 μg/L), have reported higher concentrations [3,6]. Since microplastics have permeated all parts of the world, their environmental prevalence has been widely reported in other regions. In China, 379-7924 microplastic particles were detected in the Guangzhou section of the Pearl River [7]. The marine environment east of Japan contained 26-228 microplastics/m^2 [8]. A coastal area in the Northern Gulf of Mexico, USA, was reported to have 5-117 microplastics/m^2 [9]. 0.01 to 0.41 microplastics/m^3 were retrieved from the waters of Northwestern Australia [10]. Present calculations, grounded on the principles of mass conservation, suggest that the breakdown of microplastics into nanoplastics could result in particle concentrations that are up to 10^{14} times greater than the current globally measured concentrations of microplastics [11]. These concentrations could be even higher in areas heavily affected by plastic pollution, such as coastal shallow nearshore habitats [12,13].

Existing data suggests that microplastics can have detrimental effects on a range of marine life forms, for instance, by modifying the feeding patterns, growth, reproduction, survival, and behaviors [14,15]. However, research on the impact of these pollutants on photosynthetic primary producers, which form the base of marine food chains, has primarily concentrated on microalgae [16–18]. These studies have found that microalgal growth and photosynthesis are negatively affected due to factors such as physical adhesion of particles to cell surfaces, obstruction of light and nutrient intake, water cloudiness, damage to cell membrane structure and DNA, and the release of toxic additives [19,20]. The external adsorption of microplastics on macroalgae and the subsequent transfer of microplastics from macroalgae to consumers have also been documented [21]. The impacts of microplastics on microalgae have been presented in several reviews. Despite this, there are very few reviews on the impact of microplastics on rooted marine plants like seagrasses, probably because of comparatively less research in this area. With an increasing body of research suggesting that seagrass meadows can serve as long-term repositories for microplastics due to their capacity to trap particles and accumulate them in sediments, there is a need to systematically review the impacts of microplastics on seagrasses [22–24]. There is also evidence highlighting that the presence of epiphytes growing on seagrass leaves can contribute to the accumulation of microplastics [13]. Once in marine sediments, microplastics can influence microbial communities, leading to changes in nutrient cycling [25], and can increase the local concentration of sediment pollutants, acting as a carrier for heavy metals and residual monomers [26].

Microplastics could potentially interact with seagrasses at both the shoot level through the water and at the root level through the sediment. Seagrass meadows offer a variety of essential ecosystem services, such as the regulation of nutrient cycling, provision of nursery habitats, and coastal protection [27]. However, these meadows are globally endangered due to human activities and stressors related to climate change [27,28]. Consequently, it is crucial to understand the effects of microplastics on seagrass ecosystems. This review aims to provide a comprehensive overview of the fate and impacts of microplastics on seagrass ecosystems globally. Doing so contributes to greater insight into how plastic pollution influences the ecological functions of seagrasses, in addition to other stressors related to climate change and human activities that they are already facing. Furthermore, this could help in formulating effective conservation strategies for seagrass ecosystems.

To achieve this aim, this review includes 66 papers published in the past 10 years. The papers were sourced from major scholarly databases comprising Web of Science, Scopus and ScienceDirect. Keywords comprising microplastics, impacts, and seagrasses were used in the search. The Boolean search string used was (“microplastics” OR “micro-plastics”) AND (“seagrass” OR “marine plants”) AND (“impacts” OR “effects” OR “consequences”) AND (“ecosystems” OR “environments” OR “habitats”). The inclusion criteria were (1) The articles must be written in English; (2) The articles must be scholarly and peer-reviewed; (3) The articles must be published between 2014 and 2024, with focus given to those published between 2019 and 2024; (4) The articles must be related to seagrasses, seagrass ecosystems or seagrass meadows, not microalgae, macroalgae, mangroves and salt marsh plants alone. However, articles mentioning microalgae and macroalgae as parts of the seagrass ecosystem are included.

2. Seagrass meadow as a sink of microplastics

Seagrasses are commonly found in shallow waters with high light penetration, which are also where most microplastics are found. When microplastics enter the seagrass ecosystem, the above-ground biomass and complex structure of seagrass blades reduce water currents, leading to the trapping of particulate matter, including microplastics, among the blades and their eventual settling into the sediment below [29]. However, not all microplastics reach the sediment; some become part of the epiphytic communities that attach to seagrass blades (**Figure 1**) [30]. Epiphytes, which are small stationary plants like cyanobacteria, diatoms, crustose coralline algae, and macroalgae that stick to seagrass blades, provide a rough surface where microplastics can stick and get trapped. These epiphytes then grow over the trapped microplastics, keeping them attached to the blade surface. This is supported by the findings that many microplastics on seagrass blades were found within epiphyte assemblies [31,32]. New evidence also suggests a significant relationship between the abundance of microplastics and the density of epiphytes, indicating that more epiphytes on a blade directly correlate to more microplastics [13]. Some seagrass genera, specifically *Posidonia*, can trap microplastics not only within their own ecosystem but also within their aegagropilae, which are essentially a ball-shaped mass of hairlike filaments. These aegagropilae accumulate on beaches near seagrass meadows, suggesting that seagrasses may also play a role in exporting microplastics out of marine environments, in addition to trapping them within their own ecosystem [22].

Research conducted in natural environments has revealed a significant build-up of plastics within seagrass ecosystems, present both in the sediment and on the blades of seagrass (**Figure 1**). A study by Huang et al. discovered that the sediments in these ecosystems had microplastic levels that were 1.3 to 17.6 times higher than in areas without vegetation [33]. In a separate study, Huang et al. reported an enrichment factor as high as 2.9, with microplastics of fiber shape and blue color being most detected [34].

The prevalence of microplastic fibers in the seagrass ecosystems could be due to the abundance of these fibers in subtidal zones, often contributed by laundry, fishing nets, and fishing ropes [35]. Generally, in sediments and water columns worldwide, blue microplastics are found most frequently, with transparent ones being the second most common [36]. Additionally, Goss et al. (2018) detected an average of 4.0 ± 2.1 microplastics on each blade of the tropical seagrass species *Thalassia testudinum* [31]. Kreitsberg et al. also found the sediments of seagrass beds in the Baltic Sea to contain 0–1817 (with a median of 208) microplastic particles per kilogram (dry weight), a figure significantly higher than what has been previously reported from nearby unvegetated and offshore sediments [37]. However, the surface water in the seagrass beds contained 0.04–1.2 (with a median of 0.14) microplastic particles per liter, which is comparable to other regions of the Baltic Sea. Among the identified microplastic particles, blue fibers were the most common [37]. On the contrary, Unsworth et al. sampled eight seagrass meadows and their adjacent unvegetated sites across the UK to test for the presence of microplastic particles in the sediment. They found microplastics in 98% of the samples, with fibers constituting 91.8% of all identified microplastics, in line with the observation of Huang et al. [34,38]. The overall abundance was recorded as 215 ± 163 microplastic particles per kg of dry weight of sediment in seagrass and 221 ± 236 microplastic particles per kg of dry weight of sediment in unvegetated habitats. No significant differences were found in the number of microplastics in relation to vegetation, indicating a general accumulation of microplastics in the broader environment rather than the seagrass ecosystem as a concentrated sink of microplastics [38]. This could be attributed to physical and anthropogenic factors, such as local hydrodynamics and population density, that may have a greater influence on microplastic abundance in marine environments. Interestingly, Tahir et al. did not observe any significant difference between the microplastic abundance in sediment samples collected from seagrass meadows of high, medium, and low coverages in Makassar, Indonesia, indicating spatial variability of microplastic abundance and the presence of multiple factors affecting it [39].

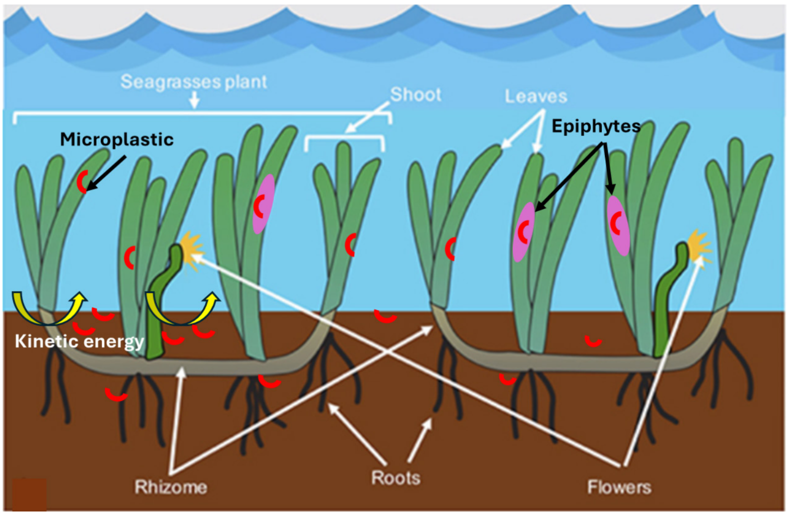

Figure 1. Distribution of microplastics in seagrass meadows. Some microplastics attach to the leaves directly while others attach to the epiphytes on the leaves. Microplastics also accumulate in the sediment, sometimes facilitated by the near-bed turbulent kinetic energy.

Compared to bare sediments, seagrass bed sediments may serve as a significant repository for microplastics. This is primarily due to the near-bed turbulent kinetic energy, which is also responsible for trapping sediment (**Figure 1**) [29,34]. This was demonstrated in an experimental study using the seagrass species *Zostera marina*, with four different canopy shoot densities (0, 50, 100, 200 shoots per m^2) to intercept microplastic particles (polypropylene, polystyrene, polyamide, and polyethylene terephthalate) with specific densities ranging from 0.90 to 1.34 g cm^{-3}. The study found that microplastic particles carried by a simulated unidirectional flow of 2 to 30 cms^{-1} were trapped in the seagrass canopies, but not in bare sand [30]. The seagrass canopies only retained floating microplastics (polypropylene) at low velocities (less than 12 cms^{-1}), due to a barrier formed by the canopy. However, sinking particles (polystyrene, polyamide, polyethylene) were retained across a broader range of flow velocities. This suggests that less dense sinking microplastic particles might escape from the seagrass canopy at high velocities, while denser sinking particles could be caught in areas around the shoots of seagrasses subjected to scouring [30]. The scouring was caused by the near-bed kinetic energy mentioned earlier. While inconsistent findings have been reported on the role of seagrass meadows as a sink of microplastics, marine canopies could serve as potential barriers or sinks for microplastics under certain bio-physical conditions, with the barrier effect increasing with the density of seagrass shoots and the specific density of the polymer, and decreasing with the velocity of the flow.

Seagrass blades with attached microplastics may also contribute to this accumulation as they shed and fall to the sediments below [33]. For instance, the turtle grass *Thalassia testudinum*, has broad, flat blades that support a variety of epibiont communities. Likewise, microplastics might gather on the blades of the seagrass (**Figure 1**). A study on the seagrass samples taken from Turneffe Atoll revealed that 75% of *Thalassia* blades had microplastics attached to them, with microfibers being more prevalent than microbeads and chips at a ratio of 59:14 [31]. Microplastics might have accumulated on the seagrass as they were trapped by epibionts or adhered through biofilms. Alarmingly, grazers were observed to consume seagrasses that had a higher density of epibionts. Moreover, the density of microplastics increases due to the formation of aggregations and associated biofilms, leading to their rapid sinking into sediments [40,41]. Given this significant accumulation of microplastics and the biodiversity within these ecosystems, it is crucial to consider the impact of microplastics on seagrass habitats [42].

3. Impacts of microplastics on seagrasses

One of the major concerns with microplastics is their propensity to absorb or form heteroaggregates with toxins, including persistent organic pollutants and nanoparticles. This happens because many pollutants are more attracted to the hydrophobic surface of microplastics than to seawater [43]. This attraction can differ among various types of plastic, as their physical and chemical properties influence their adsorption capabilities [44]. Over 78% of these pollutants are deemed harmful to marine life, and their interactions with microplastics could potentially increase their toxicity, especially towards marine algae [45]. Polluted microplastics were reported to sink in coastal marine systems where seagrass meadows are found [46]. Due to the physical characteristics of seagrasses, polluted plastics are more likely to sink within seagrass ecosystems than in nearby unvegetated sediments, probably interacting with epiphytic algae in the process [30]. Once ensnared in an epiphytic community, persistent organic pollutants and other toxins attached to microplastics can become bioavailable to algae, including those in epiphytic clusters, through desorption (**Figure 2**) [47]. This is evident in the marine algae *Chlorella* sp., which can absorb toxins carried by microplastics, including nanoparticles and triphenyltin chloride [48].

Despite the fact that the majority of microplastics on seagrass blades are attached to epiphytes, the impact of microplastics on seagrass epiphytes has been understudied [31]. Microplastics have the potential to significantly hinder the growth and photosynthesis of algae, but their overall effects on seagrasses could be more intricate. If microplastics cause a decrease in the growth and photosynthesis of epiphytes, this could actually be beneficial for the seagrass plant, as epiphytes compete with seagrasses for light, nutrients, and space [49]. A decrease in epiphytes could result in an increase in the passive diffusion of CO_2, O_2, and nutrients into the blades and a higher availability of inorganic carbon in the leaf microenvironment [49]. However, these benefits can only be realized if microplastics do not also negatively impact seagrasses. While there is limited literature on this topic, evidence suggests that this is unlikely. Microplastics that adhere to seagrass blades may physically resemble epiphytes by blocking seagrass cells, creating a shading effect, and subsequently reducing light attenuation and nutrient transfer [49]. From a toxicity perspective, microplastics could increase the local abundance of pollutants on and around seagrass blades through desorption (**Figure 2**) [47,50]. While there is no documentation yet of toxin bioavailability via microplastic desorption for seagrasses, evidence from marine and aquatic algae suggests that this pathway is possible [48,51].

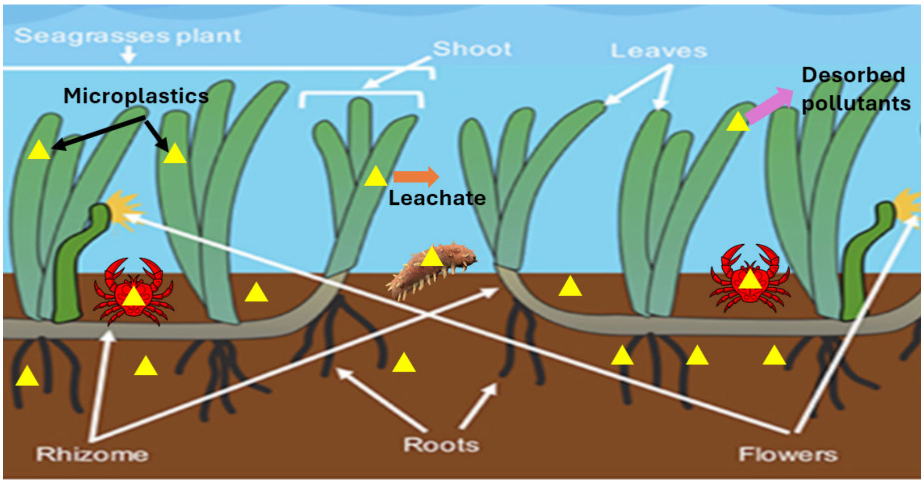

Figure 2. Microplastics themselves, as well as the additives leached and the pollutants desorbed from them, can affect seagrasses in multiple ways, depending on the tolerance of the seagrasses. Microplastics and the associated chemicals can enter the organisms dwelling in the seagrass bed and, subsequently, the food chain.

Furthermore, there is a lack of evidence indicating that epibionts affect the distribution of microplastics on seagrasses. Seng et al. measured the amount of microplastics present on the surfaces of three types of intertidal seagrasses, namely *Thalassia hemprichii, Cymodocea serrulate*, and *Cymodocea rotundata*, as well as two kinds of subtidal macroalgae, namely *Padina* sp. and *Sargassum ilicifolium*. The authors discovered that the density of microplastics was significantly greater on seagrasses compared to macroalgae. However, they did not find any correlation between the density of microplastics and the coverage of epibionts on either seagrasses or macroalgae [52]. While their research has provided preliminary evidence of the presence of microplastics on the surfaces of macrophytes in their natural environment, it does not establish that epiphytes on seagrasses decrease with increasing microplastic density.

Few studies have been conducted to examine the direct impacts of microplastics on seagrasses. Menicagli et al. demonstrated that brief exposure to high concentrations of pure polystyrene microplastics can negatively affect the seagrass *Cymodocea nodosa*, causing changes in shoot/leaf turnover, root degeneration, and oxidative stress [53]. Moreover, microplastics can hinder the photosynthetic processes of the plant. Microplastics and nanoplastics are likely to impact seagrasses via different modes. The effects of microplastics are primarily due to their adhesion to the surfaces of leaves, rhizomes, and roots (**Figure 2**), while the impact of nanoplastics is likely due to their absorption by plant tissues [53]. Another study indicates that seagrass (*Zostera marina* L.) leaves and their associated epiphytes exposed to microplastics over a short duration of 14 days were only minimally impacted. However, a gradual decrease in photosynthetic activity and respiration rates in bare seagrass leaves was observed as microplastic concentrations increased (25-1000 mg MP L^{-1}) [54]. At the highest MP exposure, dark respiration of bare leaves was reduced by more than 50%, while the respiration rates of leaves with epiphytes and separated epiphytes were reduced by approximately 45% and 30% respectively. Despite this, short-term exposure to microplastics did not affect the ability to utilize bicarbonate or the photosynthetic efficiency of *Z. marina* leaves and their associated epiphytes. The seagrass leaves (both with and without epiphytes) maintained a positive net oxygen balance across all treatments. It was hypothesized that the decrease in photosynthetic activity and respiration may be due to leachates from microplastics (**Figure 2**) [54]. This hypothesis is supported by studies on pollutants associated with microplastics, which pointed to their potential deleterious effects on seagrasses. Exposure to environmentally significant amounts of bisphenol A (BPA) has been found to adversely affect the seagrass *Cymodocea nodosa*, leading to a loss of chlorophyll auto-fluorescence and an accumulation of H_2O_2 in its cells [55]. Polycyclic aromatic hydrocarbons (PAHs) have been observed to accumulate and hinder growth in the thylakoid membranes of chloroplasts in the seagrass *Posidonia oceanica*, as well as in other aquatic plants [56].

While studies are limited and inconclusive, the adherence of microplastics to seagrass blades could generally pose a risk not only to epiphytic communities but also to the seagrasses themselves (**Figure 2**). Microplastics are likely capable of physically blocking plant cells and increasing the concentration of pollutants in the microenvironment of the blade, which could ultimately result in reduced photosynthesis and growth. The effects are likely to vary among different seagrass species with certain species more sensitive, such as *Posidonia oceanica* and *Cymodocea nodosa* than the other. The density of microplastics, when increased, could potentially escalate the concentrations of pollutants in local sediments. This is due to the role of microplastics as carriers of heavy metals, residual monomers, and various other pollutants into marine sediments (**Figure 2**) [57,58]. Microplastics, particularly polyethylene and polyvinyl chloride, have been observed to adsorb chromium, lead, and zinc significantly in aqueous environments [59]. Additionally, polystyrene microplastics were reported to adsorb organic pollutants in water such as oxytetracycline, triadimenol, and hexaconazole. Microplastics can adsorb a wide range of pollutants because of their large specific surface areas and high adsorption capacity [60]. Consequently, this might lead to an accumulation of microplastics and their associated toxins in the organisms residing in the seagrass ecosystem. These organisms include mollusks, crustaceans, and sea turtles (**Figure 2**) [13,61]. A study revealed the presence of microplastics in sea cucumbers residing in the seagrass ecosystems on the coast of Bintan Island in Indonesia, with a maximum microplastic particle of 52 per individual reported [62]. Microplastics were also found in the digestive tracts of sea hares sampled from seagrass meadows in Indonesia at an abundance of up to 73.7 particles/g [63]. In instances where the coastal water receives agricultural runoffs containing pesticides, microplastics could act as carriers of the pesticides, and their attachment to the epiphytes and seagrasses exposes these organisms to the pesticides. Herbicides targeting the Photosystem II are often found in inshore marine waters. These herbicides are typically detected in complex mixtures and are known to inhibit photosynthesis, which can lead to a reduction in energy reserves and growth in seagrass [64]. *Halophila ovalis* exposed to ten of these herbicides over a period of 24 and/or 48 hours individually at concentrations ranging from $3.5\,\mu g\ L^{-1}$ (for ametryn) to $132\,\mu g\ L^{-1}$ (for fluometuron) caused a 50% inhibition of photosynthetic activity. An additive effect was observed after the seagrass was exposed to a diuron and atrazine mixture, suggesting the additive effects posed by multiple Photosystem II herbicides to seagrasses [64].

Microplastics present in sediments could potentially affect both microbial and plant communities, especially by modifying the nutrient cycling process, which is crucial for the functioning of seagrass ecosystems. Research by Seeley et al. (2020) indicates that microplastics inhibit the processes of nitrification and denitrification in microbes living in sediments [25]. Additionally, studies suggest that microplastics reduce nutrient absorption and the ratio of shoot to root in macrophytes rooted in sediments [65]. Experiments were carried out in a controlled environment to study the impact of a biodegradable bag on *Cymodocea nodosa* at individual and community levels, involving the plant growing alone, alongside a plant of the same species, or with the seagrass *Zostera noltei*. These conditions mimicked various natural environments like bare substrate, single-species meadows, or mixed meadows [66]. After six months, the bag retained 85% of its weight while causing a decrease in the oxygen concentration and pH of the sediment's pore water. Exposing the sediment to the bag led to an increase in the root spread and vegetative recruitment of *C. nodosa* compared to the control group. Competitive interactions were observed between the same and different species of seagrass. The ramet growth pattern of the mixed meadow with *Z. noltei* changed from widely spaced to closely spaced, leading to a more compact community [66]. This aligns with the potential alteration of sediment geochemistry suggested by other studies, which potentially results in changes in the distribution of and relationship between seagrasses.

4. Conclusion

Microplastics found in seagrass sediments and blades could potentially disrupt ecosystem functions due to their chemical and physical properties. They could affect the photosynthesis and growth of epiphytes and seagrasses, nutrient cycling, and the health and function of sediment organisms. The impact could be even more significant given the high efficiency of seagrasses in trapping microplastics and their dense and diverse flora and fauna. While some studies did not observe significant differences in microplastic abundance in seagrass-vegetated and the surrounding unvegetated sediments, most studies indicate that seagrass meadows act as a sink of microplastics. With the potential ability to concentrate microplastics, it is possible that the current microplastic concentrations in seagrass sediments are adversely affecting many vital ecosystem functions, including microbial and plant nutrient dynamics, and sediment organism functions. Furthermore, the presence of biodegradable plastics in seagrass sediments was found to alter the interactions and distribution of seagrass species. This could be attributed to the alteration of sediment geochemistry. Microplastics are likely to impact the epiphytes growing on seagrasses, which, in turn, affect seagrasses. Indirectly, the leaching of chemicals from microplastics and the desorption of environmental chemicals sorbed on microplastics could adversely affect the health of seagrasses.

The existing research in this genre has placed an emphasis on documenting the presence of microplastics in seagrass ecosystems and understanding how they accumulate. However, with microplastics now widespread in seagrass meadows and unlikely to be removed, the focus of research needs to shift towards understanding the impacts of this accumulation. As data on microplastic quantities in various seagrass species becomes increasingly available, it will be possible to study the impacts of microplastics on photosynthesis and growth of epiphytes and plants, nitrogen and carbon cycling, and the health of sediment organisms using environmentally relevant concentrations under controlled conditions. This review contributes significantly to highlighting the major gap in research related to the impacts of microplastics on seagrass ecosystems. It provides greater insight into how microplastics interact with seagrass ecosystems through their potential function as a microplastic sink.

Conflict of Interest

The author declares that there are no known conflicts of interest.

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