frontiers | Frontiers in Environmental Science

TYPE Review
PUBLISHED 18 August 2025
DOI 10.3389/fenvs.2025.1635230

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OPEN ACCESS

EDITED BY
Hongli Tan,
Jinan University, China

REVIEWED BY
Pengfei WU,
Nanjing Forestry University, China
Oscar Manuel Rodriguez Narvaez,
Centro de Innovación Aplicada en Tecnologías Competitivas (CIATEC), Mexico

*CORRESPONDENCE
Wael Hamd,
wael.hamd@balamand.edu.lb

RECEIVED 26 May 2025
ACCEPTED 29 July 2025
PUBLISHED 18 August 2025

CITATION
Bel Hassen M, Bellaaj Zouari A, Abdennadher M, Assaf J-C, Nakad M, Abboud R, Khammeri Y, Banni M, Panzeri A, Gomes L and Hamd W (2025) Plastics pollution: pathways, impacts, and regulatory challenges in marine environments.
Front. Environ. Sci. 13:1635230.
doi: 10.3389/fenvs.2025.1635230

Plastics pollution: pathways, impacts, and regulatory challenges in marine environments

Malika Bel Hassen[1], Amel Bellaaj Zouari[1], Moufida Abdennadher[1], Jean-Claude Assaf[2], Mantoura Nakad[3], Rami Abboud[3], Yosra Khammeri[1], Mohamed Banni[4], Alberto Panzeri[5], Leonardo Gomes[6] and Wael Hamd[2]*

[1]Laboratory of Marine Environment, National Institute of Marine Sciences and Technologies, Tunis, Tunisia, [2]Chemical Engineering Department, Faculty of Engineering, University of Balamand, El-Koura, Lebanon, [3]FOE Dean's Office, Faculty of Engineering, University of Balamand, Kelhat, Lebanon, [4]Laboratory of Agrobiodiversity and Ecotoxicology LR21AG02, Sousse University, Sousse, Tunisia, [5]DNV Business Assurance Italy S.r.l., Milan, Italy, [6]HOLOSS – Holistic and Ontological Solutions for Sustainability, Avenida Afonso III, S/N – Edifício do Cais da Antiga Estação da CP, da União de Freguesias de Monção e Troviscoso, Viana doCastelo, Portugal

This review synthesizes existing literature on microplastics in marine ecosystems from various oceanic regions. Microplastics in marine environment originate from a range of sources, including land-based activities, rivers inputs and oceanic-based sources such as fishing, aquaculture, tourism and extreme oceanic events. Methodological and technical limitations, like sampling, identification and quantification, as well as data reporting and analysis, are key constraints in microplastics research, making it difficult to evaluate plastic debris volume in different marine environments. Microplastics have colonized diverse oceans, even polar areas. Their spatial distribution is influenced by their physicochemical properties as well as factors influencing their transport including wind driven waves, current and colonization by microorganisms. The most prevalent polymers in various oceanic systems are PE, PP, and PS, accounting for more than 60% of recovered microplastics. Microplastics affect both unicellular and multicellular marine organisms at various structural levels, causing significant disruptions that negatively impact their ecological and biological functions as well as their social behavior. This threatens both human and ecosystem health. Microplastics significantly impact marine ecosystem services, with total potential losses estimated to be between 1.18 and 2.16 trillion USD, accounting for about 2% of global GDP. Microplastics impair blue carbon ecosystems, reducing their carbon sequestration capacity and exacerbating the economic costs associated with climate regulation and coastal protection. The existing regulatory frameworks addressing plastic pollution are synthesized to identify gaps and highlight opportunities for enhancing and implementing more effective, evidence-based regulations that promote environmental sustainability.

KEYWORDS

microplastics, pathways, accumulation, impacts, ecosystem services, policies and regulations, sustainability

1 Introduction

Global plastics production reached 390.7 million tons at the end of 2021, with nearly 80% of these plastics are likely to end up in natural environment (Plastics Europe, 2020). In 2019, approximately 40% of plastics in the EU-28 were used for packaging, a significant portion of which was designated for food-related applications including single-use plastic products for food and beverage containers (Plastics Europe, 2021). Global greenhouse gas emissions from the production, use and End-of-Life (EoL) treatment of conventional plastic were estimated at 1.7 Gt CO_2-eq. Without changes in plastic use strategies, this figure is expected to increase to 6.5 Gt CO_2-eq by 2050 (Zheng and Suh, 2019).

Beyond their carbon footprint, plastics generated on land ultimately accumulate in the oceans, which act as the final sinks for this persistent pollution and pose a significant sustainability challenge. While the mechanism by which they reach the ocean could be different, the main pathway is through a transit of urban rivers network (Lebreton et al., 2017) (Meijer et al., 2021), facilitated by various means such as atmospheric inputs, population size and quality of waste management systems (Dris et al., 2016) (Jambeck et al., 2015) (Murphy et al., 2016). Numerous studies have reviewed the origin of plastic and their main pathways from land to marine ecosystems (Habumugisha et al., 2024) (Belli et al., 2024). There is a broad consensus that 70%–80% of ocean plastics originate from land-based sources, while 20%–30% come from marine sources (UNEP, 2022), with fisheries being a direct contributor (Lebreton, 2022). Other sources, like the atmospheric input, has also been reported (Liss, 2020) with a microplastic (MPs) residence time in the atmosphere ranging from minutes to days (Evangeliou et al., 2022).

Plastics are subject to degradation and continuous fragmentation due to factors such as oxidation, UV radiation, and biological effects (Andrady et al., 2015) (Zbyszewski et al., 2014) (Zettler et al., 2013). These degradation processes result in the continuous fragmentation of plastics, breaking larger macroplastics (MAPs) (>25 mm) into (MPs) (<5 mm) and eventually into nanoplastics (NPs) (<1 µm) (Gigault et al., 2021) (Zhao K. et al., 2022). The small sized fractions, i.e., the micro and nano sized plastics have been considered as emerging pollutants, threatening aquatic life and human health (Hamd et al., 2022) (Eerkes-Medrano et al., 2015). Microplastics, the most extensively studied of these small particles, appear in various shapes in the environment. They originate either as primary MPs, intentionally manufactured for products such as personal care items, fertilizers, paints, detergents, and cleaning agents, or as secondary MPs resulting from the breakdown of larger plastics (Dris et al., 2016) (Jambeck et al., 2015) (Andrady et al., 2015) (Uheida et al., 2021) (Dris et al., 2018; Cole et al., 2011). Despite the growing awareness of MPs as significant emergent pollutants, there remains a substantial knowledge gap regarding their specific sources, characteristics and complex factors influencing their behavior, and fate in the marine ecosystem. The quantities of plastic amount reaching the ocean has been estimated in several studies (Lebreton et al., 2017) (Jambeck et al., 2015) (Schmidt et al., 2017). Overall, estimates suggest a maximum value of 14 Mt/year, accounting for about 3% of all plastic production (Jambeck et al., 2015). Nevertheless, lack of standardization in research methodologies and findings strongly complicates the assessment of MPs abundance and distribution (Jolaosho et al., 2025).

Additionally, MPs have detrimental effects on natural ecosystems. It endangers marine species ranging from top predators to invertebrates as well as microorganisms, causing injuries, impaired mobility, and even death. Furthermore, when ingested, it causes internal injuries, malnutrition, and toxicity (Kühn et al., 2015) (Li et al., 2016) (Abouda et al., 2022) (Zitouni et al., 2021) (Missawi et al., 2021). Therefore, MPs pollution can negatively impact ecosystem structure and functions, thereby impairing ecosystem's ability to provide essential services to human societies. These services include provisioning services such as food supply (e.g., fish and shellfish) and raw materials (e.g., seaweed); regulating services like water purification and climate regulation (e.g., disruption of carbon sequestration); supporting services like habitat provision, biodiversity conservation, and nutrient cycles; and cultural services particularly recreation and education (Reid et al., 2005).

Building on the detrimental effects of MPs on marine life and ecosystems, their proliferation poses a significant threat particularly to valuable Blue Carbon Ecosystems, such as mangroves, seagrasses, and salt marshes (Yu H. et al., 2021) (Ogbuagu et al., 2022). These coastal and marine habitats play a crucial role in mitigating climate change as they capture and store significant amounts of carbon dioxide from the atmosphere (Macreadie et al., 2017) (Mcleod et al., 2011). The infiltration of MPs into these blue carbon environments disrupts their health and function (Lau et al., 2020) (Zhou et al., 2023) by affecting not only the organisms residing within these habitats but also their abilities to sequester carbon, ultimately reducing the ecosystems' capacity to provide essential services.

Despite the accumulated knowledge on MPs' effects on marine ecosystems, there is a lack of comprehensive analyses integrating and synthesizing current literature on the various impacts of MPs on both marine life and ecosystem services. This gap limits our understanding and assessment of the actual threats that MPs present to marine environments. Therefore, this review intends to fill these gaps by providing a holistic analysis of MPs impacts, with a focus on the losses that this pollution causes to marine ecosystem services. Furthermore, the review examines the socioeconomic and sociocultural implications of plastic pollution and provides an evaluation of existing policies and regulations with a sustainability perspective. It aims to consolidate existing knowledge and offer a new insight into the full spectrum of MPs pollution's impacts on environmental and socio-economic aspects, including the regulatory framework, by providing a detailed overview to enhance understanding and guide future environmental management and policy efforts.

2 Microplastics sources and pathways to marine environment

The main sources, fate, transport pathways and routes of MPs must be well explored and detailed to reasonably comprehend and prevent contamination in the marine environment. In this section, we investigate MPs' main origins and how they get into the marine environment. The fate and transport of plastics particles to the marine environment depend on several land-based sources, rivers inputs and marine and maritime activities (Lebreton and Borrero, 2013). The ratio of cities to-rivers-to-shipping lanes was established at 40:40:20% (Lebreton et al., 2012). This ratio could be adjusted to 50:30:20% (Liubartseva et al., 2018) depending on the city' capacities in terms of population density, level of urbanization and number of rivers.

2.1 Land-based sources

Land-based MPs sources are diverse and include landfills, wastewater solids and effluents, industrial facility losses, plastic agricultural mulch, polymer paints, and vehicle tire abrasion (Chae and An, 2018). Other sources have also been identified, such as MPs from washing textiles, burning plastics and atmospheric deposition (Hale et al., 2020). In most countries, plastics are dumped in landfills, either in closed or open-air facilities. Environmental problems arise when there are offsite losses or mismanaged waste including the release of plastics during transportation and disposal, as well as from municipal solid waste collection and processing. In addition, dumps installation close to coastal areas are subject to sea level rises, flooding and erosion, contributing to additional release of plastic debris in the environment (Hale et al., 2020).

Furthermore, synthetic fibers released during washing textiles have been identified as useful particles that could be used as markers of wastewater outfalls and land application of biosolids (Habib et al., 1998). Given the differences in sampling techniques and analytical methodologies, it has not been feasible to achieve consensus regarding the most prevalent types of MPs in the environment. However, the IUCN has identified synthetic textile releases from laundry as the leading source, contributing 35% of the ocean MPs load (Boucher and Friot, 2017). These MPs often escape treatment facilities in developing countries and may directly enter streams and reach the marine environment, where they undergo a long biodegradation process, indeed only 4% of polyester show biodegradation after 243 days of exposure (Hale et al., 2020).

Additionally, tire wear in vehicles is another source of MPs from terrestrial environments. Modern tires incorporate fillers such as carbon black, metallic fibers, additives, and polymeric materials combined with rubber, predominantly composed of butadiene and styrene-butadiene polymers. Together, these components serve as significant sources of secondary MPs. According to Kole et al. (2017), Americans generate on average approximately 4.7 kg of tire-wear MPs annually, which amounts to approximately 1.8 million metric tons. They posited that tire degradation may contribute 5%–10% of MPs entering global oceans. These particles infiltrate waterways via surface runoff, enhanced by the impermeability of road surfaces, or through entry into sewer systems, followed by further processing in wastewater treatment facilities (Hale et al., 2020); (Jolaosho et al., 2025). Sewage treatment facilities are major accumulators of MPs. It has been indicated that the annual input of MPs from sewage sludge to cropland in Europe and North America could exceed the overall concentration of MPs in the ocean surface water (Nizzetto et al., 2016). In sewage treatment, MPs cannot be completely removed. The removal rate can reach up to 90% after a complete treatment process (Pivokonský et al., 2020). However, depending on the treatment efficiency, some nano and/or micro-plastic residues remain discharged in wastewater effluents (Ziajahromi et al., 2017). Particularly, treatment may be less effective for MPs <100 μm. Murphy et al. (2016) noted that most of the buoyant MPs, including the majority of microbeads from personal care products, were entrained in the floating grease fraction. As consequence, the exclusion of oil and grease and primary sludge from land applied materials would thus reduce the quantity of MPs transferred to soils and this ending up into the aquatic ecosystem.

Microplastics particles can adhere to soil when irrigated with treated wastewaters, making the soil a sink for MPs that accumulate overtime (Boughattas et al., 2022) (Hattab et al., 2024a) (Zhang et al., 2022). They can move downward with percolating water and finally reach groundwater reservoirs or surface water bodies, contaminating the whole ecosystem (Dube and Okuthe, 2023). Soil-based water infiltration and cultivations practices were also identified as potential sources of MPs (Habumugisha et al., 2024), due to the use of mulching films in agricultural soils which are very common but they are difficult and expensive to recycle (Petersen and Hubbart, 2021). With less than 60% of plastic film being recovered (Zhaorong et al., 2020), residue from these films has become a major source of soil MPs (Boughattas et al., 2022), leading to the accumulation of plastic particles in or on the soil. Additionally, compost application, could also be a source of MPs to the soil (Zhang et al., 2022). It has been reported that inefficient waste and manure management practices can lead to plastic contamination of composts (Vithanage et al., 2021). MPs contaminated compost can adversely affect soil living organisms such as the earthworm *Eisenia andrei* causing cytotoxicity, genotoxicity, and neurotoxicity (Hattab et al., 2024b).

To date, little research has examined the atmospheric transport of MPs. The airborne MPs can be transported to ocean surface air and remote areas. Indeed, many airborne MPs (365 items m^{-2} day^{-1}) were recorded in the pristine mountainous area (French Pyrenees) (Allen et al., 2019). Brahney et al. (2020) show that even the most isolated areas in the United States (national parks and national wilderness areas) accumulate MPs particles after being transported by wind and rain. They estimate that more than 1,000 metric tons per year fall within south and central western U.S. protected areas. Most of these plastic particles are synthetic microfibers used for making clothes. Airborne MPs can be ingested and inhaled by humans, thus allowing MPs to enter the digestive and respiratory systems. Inhalation of MPs, especially through indoor air, contributes to higher human exposure to MPs compared to other routes of exposure imposing a potential health risk. According to Wang et al. (2019), there was a moderate increase in MPs atmospheric levels in Shanghai, where fibers accounted for 67% of the particles. As a result, the population was predicted to inhale about 21 MPs particles per day.

The investigations of the main potential sources of airborne MPs, indicate the degradation of large plastics, industrial emissions and dust resuspension (Dris et al., 2016) (Liu et al., 2019a). The use of *in situ* observations of MPs deposition combined with an atmospheric transport model to identify the most likely sources of atmospheric plastic over the land regions of the western United States, suggests that atmospheric MPs are primarily derived from secondary re-emission sources including roads (84%), ocean (11%), and agricultural soil dust (5%) (Brahney et al., 2021). Once in the atmosphere, suspended MPs are

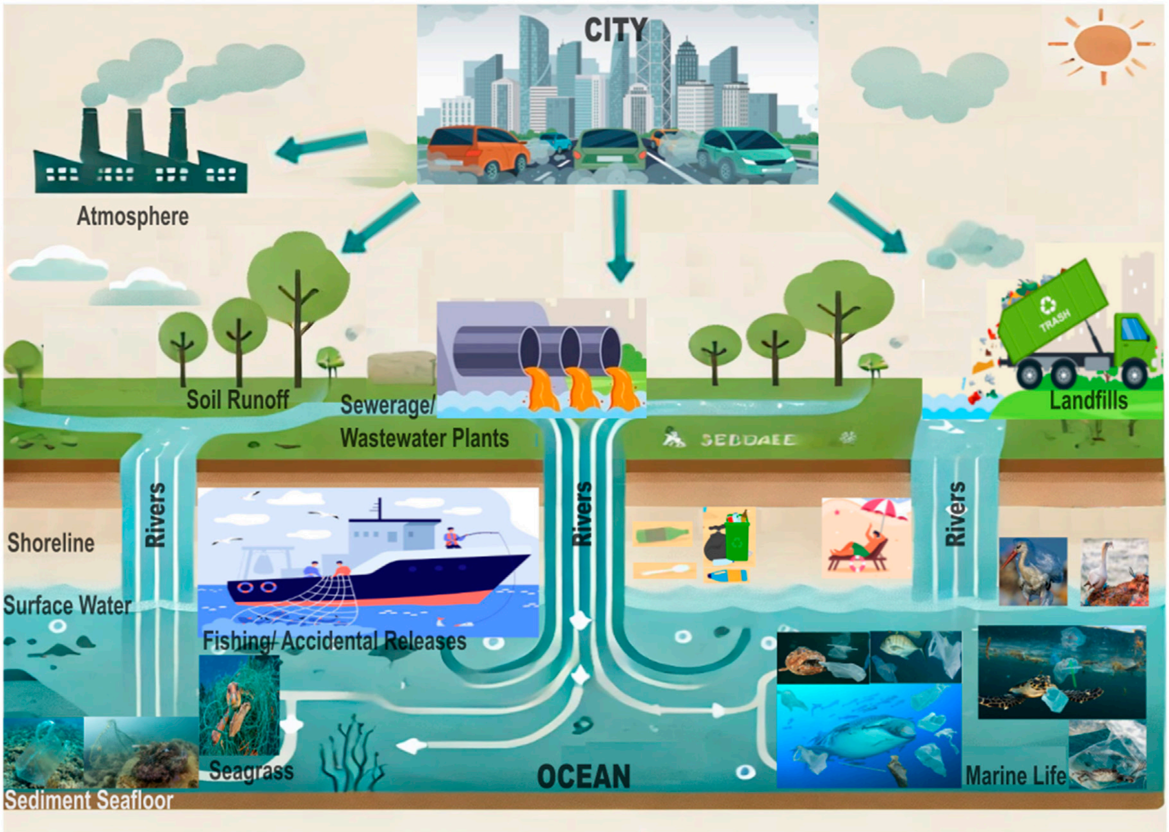

FIGURE 1
Diagram of plastic waste main sources and pathways to the ocean final sink.

transported passively by wind effects, their transmission distance has been approximately estimated to 95.0 Km in 5 months (Allen et al., 2019). Some oceanic areas can be highly impacted by suspended atmospheric MPs deposition such as the West Pacific Ocean (Liu et al., 2019b), however due to the lack of assessment initiatives, little is known about the quantities deposited in other oceanic regions.

2.2 Rivers input

Terrestrial inputs are assumed to enter the ocean primarily at coastal release points corresponding to major rivers as shown in Figure 1.

Surprisingly, research on plastic pollution in freshwater ecosystems, such as rivers, is far less common than that in marine ones. Particularly River sampling is especially inconsistent due to a lack of dedicated efforts, particularly in extremely polluted rivers such as those in Asia (Blettler et al., 2018). As a result, most studies have often used several approximations to estimate riverine input fluxes. For instance, Jambeck et al. (2015) and Lebreton et al. (2017), predominantly based their global estimates of plastic emission fluxes on the volume of mismanaged plastic waste and the likelihood of its entry into aquatic ecosystems (Lebreton et al., 2017) (Meijer et al., 2021). More recently, Meijer et al. (2021) considered both climate and geographical factors to calculate the probability for plastics entering rivers and oceans globally. According to their estimation, over 1,000 rivers generate between 0.8 and 2.7 million metric tons of plastics emission flux per year. Zhang et al. (2023) applied a top-down methodology to estimate the global discharge of plastic using ocean transport models and a dataset of sea surface plastic concentrations. Their results indicate a yearly plastic emission flow between 0.13 million to 3.8 million metric tons.

The majority of primary MPs in European rivers were from the industry sector, personal care items and cleaning products, whereas secondary MPs were fibers from synthetic textiles (Gao et al., 2024). In Asian rivers, a significant increase in MPs concentrations was pointed out near large cities, but not all studies were able to clearly link MPs concentration to factors such as population density or industrial activities (Lin et al., 2024). In this region of the world, there is a need to shift the focus from merely reporting MPs concentrations towards investigating the relationships between anthropogenic causes and MPs riverine concentrations to identify potential pollution sources.

2.3 Ocean-based sources

Commercial fishing and recreational, tourism, aquaculture and maritime activities, such as oil platforms, can all be direct causes of MPs pollution in the ocean, endangering both marine life and vegetation (Ziani et al., 2023).

Fishing gear used for direct capture contributes to local and regional marine pollution. Hence, damaged, undesired, or no longer usable plastic fishing gear (e.g., nets, lines, buoys) often end up in the ocean through accidental loss or disposal. This abandoned, lost, or otherwise discarded fishing gear is considered the major contributor to sea-based sources of marine plastic debris (UNEP, 2022), accounting for 10% of marine plastic waste and containing the highest proportion of MAPs and mega-plastics (>50 cm) floating in the ocean. This is in line with the findings of Galgani et al. (2015) affirming that fishing nets, as well as small unidentifiable pieces of plastic represent among the largest proportion of marine litter. Investigations into the origin of the debris based on label recognition in the North Pacific Ocean, which is considered as a hotspot of MPs accumulation, reveal that most of the objects come from major fishing nations (Lebreton et al., 2022). Additionally, untreated sewage dumping in areas more than 12 nautical miles from the nearest land, which is officially authorized by the International Maritime Organization, contributes to MPs enrichment, as previously reported for wastewater.

Extreme events like tsunamis can inject considerable amounts of debris into the oceans. For instance, the 2011 Great Japan Tsunami washed away an estimated five million tons of debris into the Pacific (Murray et al., 2018). This was more than 3,000 times the average annual amount of land-based litter contributed by all of Japan (Lebreton and Borrero, 2013). The bulk of this tsunami debris will eventually accumulate in the North Pacific Ocean subtropical gyre, increasing the concentration of debris in the so-called 'Great Pacific Garbage Patch', where some of which will breakdown into tiny particles and be consumed by marine organisms.

3 Microplastics characterization and distribution

3.1 Sampling identification and quantification

The accurate quantification of MPs prevalence is greatly hampered by the current methodological and technical limitations, as well as data reporting and analysis. Across the accumulated literature the most commonly used sampling methods are manta nets, neuston nets, plankton nets, and underway pump systems (Belli et al., 2024) (Mutuku et al., 2024). The mesh sizes generally ranged from 30 to 700 µm, with 330 µm being the most common among all the sampling methods (Jambeck et al., 2015) (Belli et al., 2024) (Mutuku et al., 2024). More than 80% of field studies only sampled MPs larger than 300 µm (Conke and Nascimento, 2018); therefore, MPs smaller than this size, including 95% of cosmetic microbeads, synthetic microfibers, and secondary MPs with diameters less than 300 µm, are absent from MPs datasets.

However, microplastics smaller than 300 µm are more easily absorbed by organisms. This bias could have implications on toxicity assessments since in the small micron range, MPs could penetrate body barriers and cell membranes, potentially inducing molecular perturbations (Jani et al., 1992).

Moreover, the complexity in comparing studies on MPs in surface water, is primarily attributed to the wide diversity of sampling methodologies employed, particularly in terms of mesh size and reported particle size (Strafella et al., 2022). Hale et al. (2020) have shown a massive distortion in the size distribution of MPs in surface water when comparing two datasets using different sampling techniques, i.e., pumped surface water through a 10 µm filter vs. thawing a 200 µm net. Furthermore, even after elimination of all technical sampling constraints, the MPs surface water distribution, which is justified historically and practically by a visual appreciation of the phenomenon, is challenged by the sample's representativeness, since most of the plastic pool in the ocean is either bio-fouled or sinking to the sea bottom. Indeed, 94% of plastic waste in marine environment is deposited on the seafloor, with only 1% is found on the ocean surface (Sherrington, 2016).

Numerous analytical methods have been employed for the quantification and identification of MPs in the environment (Lu et al., 2021). Early approaches often relied on optical microscopy. However, this technique cannot determine chemical composition and is therefore of limited use in differentiating effective synthetic polymers from sample interferences.

For polymer identification, Fourier transform infrared spectroscopy (FTIR) has been widely used and has significantly improved capabilities for MPs characterization. Currently, the FTIR combined with microscopy are predominantly utilized in marine environment studies (Belli et al., 2024) (Mutuku et al., 2024). However conventional FTIR is generally limited to particles larger than 10 µm, due to diffraction constraints. Raman micro spectroscopy, which allows a detection size of less than 1µm, is increasingly used (Schymanski et al., 2018). Some other cutting-edge techniques for MPs identification and characterization have also been used such as pyrolysis gas chromatography and liquid chromatography mass spectrometry (Schymanski et al., 2018). Generally, studies opted for a combination of techniques to broaden the spectrum of their findings, acknowledging the complementary strengths of each method (Da Costa et al., 2020).

In summary, although analytical approaches have rapidly advanced in the past decade, yet they still fail to fully meet the challenges presented by MPs (Lu et al., 2021). The main reported constraints are related to plastic particle size, namely, the nano-sized fraction as well as polymer types and chemical alterations.

3.2 Chemical composition

The major plastic polymers used in the manufacturing industry are polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS), polyurethane (PUR), and polyvinyl chloride (PVC) (Lamichhane et al., 2023). These polymers constitute nearly 90% of all plastics produced worldwide. Globally, studies have identified PE, PP, and PS as being predominant in surface waters (Table 1) due to their lower densities of 0.90–0.97, 0.91–0.92, - 1.04 and 1.10 g/cm^3, respectively (Li Y. et al., 2024) (Jolaosho et al., 2025). A consistent prevalence of five polymers PE, PP, PET, PS, and Polyphthalamide (PPA) in comparable proportions across all oceans have been reported (Mutuku et al., 2024), with PP, PE and PS accounting for more than 67% of recovered polymers. The crystallinity of these plastic polymers enhances their rigidity by improving structural integrity and resistance to deformation. More specifically, the crystallinity of PE ranges from 60% to 70% justifying its used in the production of

TABLE 1 Overview of observed and modeled MPs counts in different marine ecosystems: Item density, plastics format and predominant chemical characteristics are indicated. The following abbreviations are used PE: Polyethylene; PET: polyethylene terephthalate; PP: Polypropylene; PA: Polyamide; PPA Polyphthalamide; PS: Polystyrene; PU: Polyurethane.

Location	Sampling method	Mesh size (µm)	Unit	Items density	Particle size (mm)	Format	Polymers	References
Atlantic Ocean								
Argentinean continental shelf	Manta net	350	items.m^{-3}	0.14 ± 0.08	<1	Fibers	-	Ronda et al. (2019)
Continental shelf off the south coast of Brazil	Manta net	330	items Km^{-2}	4,461 ± 3,914	-	Fragments	PA, PU	Ronda et al. (2019)
Amazon Continental Shelf, Brazil	Bucket and filtered by plankton net	64	items.m^{-3}	3,593 ± 2,264	<0.5	Fibers	PA, PU	Queiroz et al. (2022)
North Atlantic subtropical gyre	Manta net	335	items.m^{-3}	0.62 ± 0.52	1–4.74	Fragments	PE, PP, Acrylic	Courtene-Jones et al. (2022)
Mean Atlantic Ocean*			items.m^{-3}	4.98		Fragments	PE, PET, PP	Mutuku et al. (2024)
Arctic								
Northeast Greenland Sea	underway pump systems		items.m^{-3}	2.4	0.5–5	-	PP, PA, PE, PVC, Acrylic	Morgana et al. (2018)
Arctic polar water	Manta net		items Km^{-2}	28,000	<5	-		Lusher et al. (2015a)
Pacific Ocean								
Great Pacific Garbage Patch (North Pacific subtropical gyre)	Manta net	500	items Km^{-2}	678,000–2,400,000	0.5–5	-		Lebreton et al. (2018)
North Pacific subtropical gyre	Plankton net		items Km^{-2}	10^5–10^7	<5	-		Van Sebille et al. (2015)
Northeastern Pacific Ocean	underway pump systems		items.m^{-3}	8–9,200	0-1-1	Fiber/filament, fragment, pellets and thin films	-	Desforges et al. (2014)
Northwestern Pacific Ocean	Manta net	330	items Km^{-2}	6.2 × 10^4	<1	Granule, Sheet, film and line	PE, PP, PA, PVC, PS	Pan et al. (2019)
Tropical North Pacific	Bongo zooplankton net	200	items.m^{-3}	<0.018	0.2–0.35		PE, PET, PP, PVC, Nylon	Yuan et al. (2023)
Mid-West Pacific	Manta net	333	items Km^{-2}	6,028-98,335	0.3–2.5	Fiber/filament, fragment, film granule	PP, PE, PS, PET	Xiong et al. (2025)
Mean Pacific Ocean*			items.m^{-3}	1.49		Fragments	PPA, PS, PET	Mutuku et al. (2024)
Indian Ocean								
Reunion Island (southwest part of the Indian Ocean)	Manta net	500	items Km^{-2}	4,025 ± 4,760 (East) and 10,693 ± 11,275 (West)		-	PE, PP	Sababadichetty et al. (2024)
North Indian Ocean (Bay of Bengal and Arabian sea)	Manta net	330	items Km^{-2}	15,200 -72,381	0.5–5	Fibers	PE, PP	Janakiram et al. (2023)
Eastern Arabian Sea	Bango net	333	items.m^{-3}	0.002–0.046	0.5–5	Fibers, Fragments, Film	PP, LDEP, NY	Naidu et al. (2021)
Indian Ocean	Plankton net		items Km^{-2}	10^2–10^5	-			Van Sebille et al. (2015)

(Continued on following page)

TABLE 1 (*Continued*) Overview of observed and modeled MPs counts in different marine ecosystems: Item density, plastics format and predominant chemical characteristics are indicated. The following abbreviations are used PE: Polyethylene; PET: polyethylene terephthalate; PP: Polypropylene; PA: Polyamide; PPA Polyphthalamide; PS: Polystyrene; PU: Polyurethane.

Location	Sampling method	Mesh size (µm)	Unit	Items density	Particle size (mm)	Format	Polymers	References
Tropical Indian Ocean	underway pump systems		items.m^{-3}	8–132	-	Fibers	Acrylates/PU	Hildebrandt et al. (2022)
Mean Indian Ocean*			items.m^{-3}	3.17	-	Fragments	PP, PPA, PE, PS	Mutuku et al. (2024)
Mediterranean Sea								
Gulf of Gabes	Manta Net	200	items Km^{-2}	312,887 and 77,110	<1-3	Fragments	PE, PP	Ben et al. (2022)
Gulf of Lion	Manta Net	780	items Km^{-2}	6×10^3–1×10^6	1.48 ± 0.88			Schmidt et al. (2018)
W Mediterranean	Manta Net	335	items.m^{-3}	3.52 ± 8.81	-	Fragments	PE	Fagiano et al. (2022)
Central W Mediterranean	Neuston Net	200	g Km^{-2}	$6.72 \pm 1.5 \times 10^4$	0.2–0.5	Fragments	PE, PP	Suaria et al. (2016)
Southern Mediterranean/Bizerte lagoon	Niskin bottles		items.m^{-3}	453 ± 335	-	Fibers	PE, PP	Wakkaf et al. (2020)
Medium Mediterranean Sea*			items Km^{-2}	8.48 10^4				Simon-Sánchez et al. (2022)

food wraps, vehicle fuel tanks, and industrial pipes (Hadiyanto et al., 2021). The chemical composition of PP and PE made of polyolefins with considerably long linear hydrocarbon chains can take decades to centuries to naturally disintegrate. In addition, their chemical and physical properties, such as resistance to heat, weather, fatigue, durability, and toughness, all contribute to their limited degradability (Jolaosho et al., 2025). Consequently, this plastic pollution will persist in the environment giving the slow disintegration processes. Polymers with lower density than seawater (mostly as PP and PE) will remain floating in the surface water, carried out by the surface currents and accumulated in central zones, particular gyres and convergent zones (Van Sebille et al., 2020). The polymers with high densities compared to ocean water such as PET, PVC and PC, once introduced into the marine ecosystem will directly sink to the ocean seafloor (Engler, 2012) thus become less accessible and almost impossible to eliminate suggesting that physical elimination of MPs from the marine environment is both technically and economically not feasible.

3.3 Prevalence and distribution

A comparison of MP concentration, prevalence and distribution was carried out in various marine ecosystems (Table 1). It is worth noting the disparities in sampling techniques between the multiple studies, namely, the differences in net mesh sizes and reported units. Thus, the absolute volumes of plastic debris across different marine environments remain largely underestimated or unknown due to a lack of standardization and homogenization efforts to address the discrepancies in the present appreciation of MPs spatial distribution.

In addition, most studied collected a one-time sample from the ocean waters, and since the surface distribution of MPs is highly influenced by the ocean circulation and the atmospheric forcings (Courtene-Jones et al., 2022), this may constrain the results reproducibility and comparability (Cowger et al., 2020). Nevertheless, through the reviewed literature, some technical compromises have been proposed to homogenize the MPs concentration units, such as converting the MPs concentration unit from items/Km^2 to items/m^3 when the net height and submersion depth of the sampling net mouth were provided, and the net had a rectangular shape (Lu et al., 2021) (Mutuku et al., 2024). Li C. et al. (2020) proposed that the varying concentrations of MPs can be converted into uniform results with similar units by exploring the size and number of MPs particles per volume (estimated average of plastic particles of 1 g/mL).

A standardized dataset established to compare the abundance and distribution of MPs in surface water across different oceans waters for the period 2010 and 2023 (Mutuku et al., 2024), revealed that mean MPs concentrations ranged from 0.002 to 62.50 items m^{-3}, with an average abundance of 2.76 items/m^3. The Atlantic Ocean, with a mean concentration of 4.98 items m^{-3} (Table 1), exhibited the highest average MPs concentration, followed by the Indian and the Pacific Ocean, while the lowest concentration was recorded in the Southern Ocean (0.04 items m^{-3}). A different pattern was reported for the period between 1971 and 2013 (Van Sebille et al., 2015), based on a separate standardized dataset coupled with statistical modeling. The Pacific Ocean showed the highest accumulated number of MPs particles, followed by the Indian and the Atlantic Oceans. These discrepancies, illustrating difficulties in conducting comparatives studies, may be explained by the substantial increase in the number of observations over the last decade, mainly in the south Atlantic (Belli et al., 2024), as well as by differences in the standardization procedures, which corrected variability associated with factors affecting both plastic concentration and samples representativeness, such as sampling year and wind speed (Van Sebille et al., 2015). The Pacific Ocean, where several studies on the spatial distribution of MPs have been conducted in various regions of this vast oceanic ecosystem (Table1), has revealed differences in the spatial distribution of MPs. The Great Pacific Garbage Patch, located in the North Pacific subtropical gyre, is considered one of the densest accumulation area worldwide, likely due to its vast area covering 1.6 million Km^2, with concentrations of millimeter-sized plastic debris frequently reaching up to 10^6 pieces Km^{-2} (Lebreton, 2022), and also the large inputs of plastic waste from the coastlines of Asia and the United States (Jambeck et al., 2015). This is higher than the Mid-West Pacific, where concentrations of less than 10^5 items Km^{-2} have been reported (Wang et al., 2020). Few studies on MPs distribution have been conducted in the Indian Ocean, mainly around the Arabian Seas, with concentrations in some regions reaching up to 10^6 particles Km^{-2} (Abayomi et al., 2017). The most common forms of plastics are fibers, fragments and films (Table 1). In the Atlantic Ocean, the numerical quantity of plastic fragments was significantly higher in the North Atlantic gyre than in the open ocean or inshore areas, which can be explained by the hydrodynamics characteristics of these features which can retain debris for extended periods (Cózar et al., 2014) (Courtene-Jones et al., 2022). In the southern Atlantic, a recent review (Belli et al., 2024) pointed out that the most polluted area in the region is the Bahía Blanca Estuary in Argentina, where MPs concentrations ranged from 5,900 to 782,000 items. m^{-3} (Fernández Severini et al., 2019), a level comparable to those found in more polluted oceanic areas (Meijer et al., 2021). As summarized in Table 1, fragments and fibers are the most common morphologies, whereas PE, PP and PA are the most abundant polymers.

The Mediterranean Sea has also been identified as one of the major accumulation zones of marine plastic waste, largely due to its semi-enclosed geography, limited water circulation, and the continuous influx of plastic waste from urban and industrial activities in the surrounding regions (Van Sebille et al., 2015). In this region, plastic concentrations in sea surface waters exhibit extremely high spatial and temporal variability, as confirmed by many field surveys (Gajšt et al., 2016) (Schmidt et al., 2017) (Suaria and Aliani, 2014). High variability in MPs levels in sea surface waters has been reported, with the Northwestern Mediterranean Sea exhibiting the lowest concentration (6.25×10^3 items Km^{-2}) (Collignon et al., 2014). In contrast, the highest values were found in the Levantine Basin, with coastal waters in Lebanon measuring up to 2.2410^6 items Km^{-2} (Kazour et al., 2019) and Turkey measuring $1.15\ 10^6$ items Km^{-2} (Gündoğdu et al., 2018). According to a dataset compiled by (Simon-Sánchez et al., 2022), the median concentration of MPs in the surface waters of the Mediterranean Sea is approximately $8.48\ 10^4$ items Km^{-2}, and the main long-term accumulation of plastic debris in the Mediterranean occurs along the coastlines and on the sea bottom. The most common forms of plastics are fragments and fibers, with PP and PE are the prevailing polymers (Table 1).

Despite the preconceived idea that Polar Regions are exempt from plastic pollution, Zarfi and Matthies (2010) have reported that between 6.2×10^4 and 1.05×10^5 tons of plastics flow annually into the Arctic Ocean. The evidence of plastics ingestion by several Arctic Seabirds (Baak et al., 2020), along with the considerable quantities of MPs found in the deep sea floor and in organisms at low trophic level (e.g., zooplankton) (Bergmann and Klages, 2012), suggests that MPs are transported to the Artic region via oceanic and/or atmospheric actions. Recent investigations have demonstrated that MPs are present in several regions of the Artic, both in the surface water and on the seafloor (Tekman et al., 2020), and their concentrations are even higher than previously reported.

3.4 Horizontal and vertical transport

The proper identification and parameterization schemes for MPs behaviors and factors influencing their transport are essential for a better understanding of MPs distribution, underlying quantifying methods (Kukulka et al., 2012) and guiding numerical modeling research of marine MPs (Cai et al., 2023).

Buoyant plastic debris with density lower than the ocean, is subjected to a wide range of physical and biological transport processes (Figure 2). The main physical forces driving the movement of MPs identified across the literature are wind-driven waves, tides, and currents (Van Sebille et al., 2020).

At large scale, circulation is driven by surface winds generating so-called Ekman drift. A sea surface under the influence of the Earth's rotation, the Ekman transport creates areas of convergences where floating plastic items will accumulate on a large scale, corresponding to the subtropical gyres (Law and Thompson, 2014). Buoyant debris, lacking sustainable degradability, can become trapped and circulate for years in subtropical oceanic gyres, contributing to persistent marine pollution. Five main garbage patches have been identified in the North Pacific, North Atlantic, South Pacific, South Atlantic and South Indian Oceans, yielding estimations of plastic mass accumulating at the ocean's surface (Van Sebille et al., 2015).

The velocity of the wind is highly related to the quantity of plastic materials recovered from the sea surface, because the wind mixing influences the vertical distribution of plastics. Based on surface and subsurface observations and a one-dimensional column model, Kukulka et al. (2012) demonstrated that plastic concentrations measured using surface tow measurements depend on wind speed because plastic pieces are vertically distributed in the mixed layer due to wind-induced mixing, leading to the conclusion that surface tow measurements significantly underestimate the total plastic content even for moderate wind conditions. Furthermore, the vertical mixing in the ocean is induced by several processes acting at different temporal and spatial scales. It can exist as coherent structures such as upwelling and down welling, fronts and turbulence-induced structures (Van Sebille et al., 2020). Particularly, the vertical turbulent mixing in the water column under the influence of the winds and the resulting wave action, are shown to be responsible of plastics debris resuspension from the seafloor (Cai et al., 2023).

Tidal currents play a crucial role in MPs redistribution within the continental shelf systems, generating turbulence near the bottom (Trowbridge and Lentz, 2018). The turbulent flows caused by tides or waves are primarily responsible for benthic particle resuspension (Li W. et al., 2022), influencing the plastic particle positioning on the

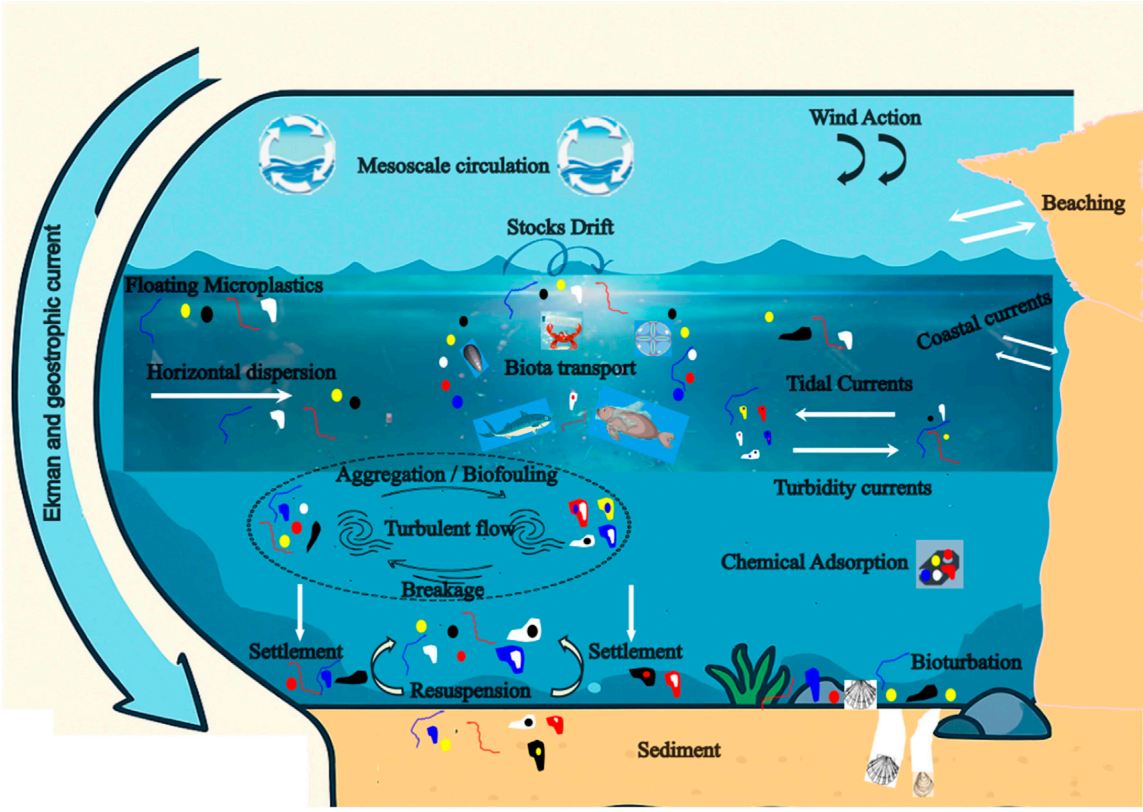

FIGURE 2
Factors influencing microplastics transport in the marine environment.

seafloor. In estuaries, tides and density fields also interact in complex ways, resulting in converging fronts or particle trapping (MacCready and Geyer, 2010), which frequently create high-concentration zones with strong tidal flows.

The fate of buoyant plastic debris in the ocean, is largely dominated by beaching onto coastlines, which removes a large fraction of floating plastic from the ocean surface (Lebreton and Andrady, 2019) (Isobe and Iwasaki, 2022). Plastic debris can also undergo changes in buoyancy due to biofouling through colonization by microorganisms such as bacteria, algae, and small invertebrates. Adhering to MPs surface, they significantly influence their transport and dispersion in aquatic environments (Anwaruzzaman et al., 2022) (Carlotti et al., 2023) (Bandini et al., 2021). MPs can also aggregate detrital materials and organic matter and concentrate in the densest planktonic layers of the water column, close to the chlorophyll maximum, thus impacting MPs settlement and accumulation (Carlotti et al., 2023). Additionally, MPs can adsorb a variety of pollutants that adhere to the surface of MPs particles through diverse processes such as ion exchange and electrostatic attraction (Yu Y. et al., 2021).

Plastic debris with a density higher than that of seawater sinks toward the seabed, considered a major sink for MPs (Woodall et al., 2014), where it can subsequently be redistributed horizontally by deep-sea circulation (Kane et al., 2020). Small MPs can also form heterogeneous aggregates favoring their settlement, owing to turbulent shear flow acting on sediments, they can resuspend thus contributing to a secondary pollution (Li W. et al., 2022). The bioturbation caused by marine organisms such as the clam behaviors, including burrowing, movement, and ingestion can provoke rapid transport of MPs to deeper layers (six to eight cm below the surface sediment) (Zhang et al., 2025).

In summary, a comprehensive and sufficient understanding of oceanographic processes and geophysical activities in surface waters is essential to apprehend aggregate abundances or concentrations of plastic in the ocean ecosystem. In addition, the MPs characteristics could be modified during the transportation processes such as transformation from micro to nano sized particles and the subsequent degradation. Therefore, extensive modeling research is needed to assess long-term changes in the transport and distribution dynamics of these particles.

4 Effects of plastic debris on organisms' biodiversity and functions

Plastics contaminate marine ecosystems across multiple trophic levels, impacting organisms ranging from phytoplankton (Hitchcock, 2022), zooplankton (Cole et al., 2013) (Alfonso et al., 2023), bivalves (Van Cauwenberghe and Janssen, 2014) (Chen et al., 2023), fish (Li J. et al., 2021), turtles (Thibault et al., 2023), marine mammals (Panti et al., 2019); and, ultimately, humans (Waring et al., 2018). Due to their ubiquity and small dimensions, MPs are easily ingested by many marine biota and transferred through food chain, which may result in bioaccumulation, referring to the

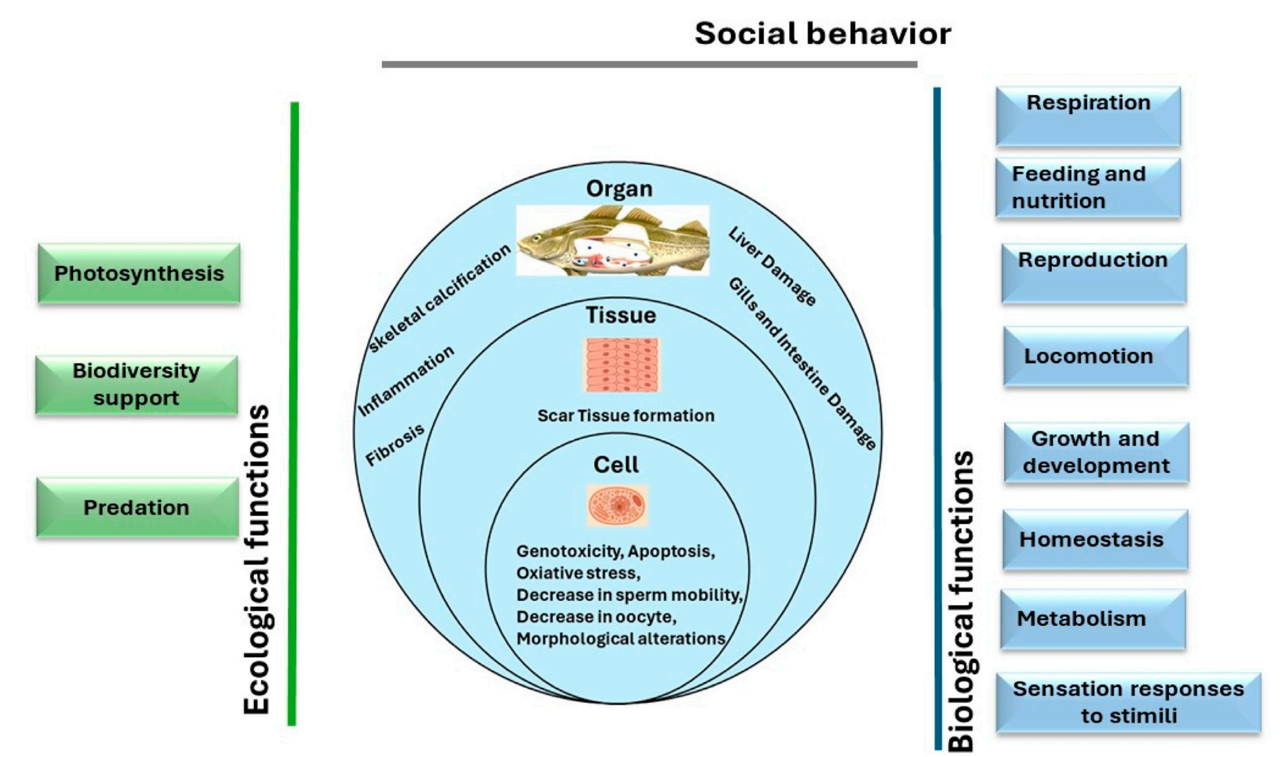

FIGURE 3
Microplastics impacts on different structural levels from cellular, tissue, organ and organ systems and the most affected functions.

accumulation of plastic particles in an organism over time (Thompson et al., 2015), and biomagnification, referring to their increase at every level of the food web (Mouat et al., 2010), leading to increased exposure of organisms at the top of the food web until they reach humans. This transfer has been experimentally demonstrated from lower to higher trophic levels with the possibility of accumulation in predators, raising concerns about the ecological and health impacts of these plastics, especially once they reach human diet via seafood intake (Farrell and Nelson, 2013) (Nelms et al., 2018) (Zhang et al., 2019).

Plastics affect both unicellular and multicellular marine organisms at multiple structural levels, including cellular, tissue, organ and organ systems, causing therefore profound disruptions like cellular alterations, tissue lesions, organ inflammation, and even physical injuries (Figure 3). In addition, plastics also disrupt the immune systems and gut microbiota. These disruptions have negative effects on biological functions like respiration, ingestion, reproduction, locomotion, and growth, ecological functions like photosynthesis and predation, and even on the scholastic behavior of these organisms. (Figure 3). In marine ecosystems, the distribution and composition of microbial communities have also been impacted by MPs, which has an effect on human and marine fauna health as well as ecosystem resilience and function. Assessing the impacts of plastics and identifying the extent of bioaccumulation and biomagnification at each stage of the food chain link up to humans will shed light on how these particles may impact humans, animals and ecosystems. Table 2 gives a summary of how plastic affects different marine organisms that are impacted by plastic contamination.

4.1 Marine organisms

The small size of MPs makes them easily mistaken for prey, leading to ingestion either through passive water filtration or feeding activity (Luís et al., 2015) (FDA, 2020). Therefore, for a number of marine species (Zitouni et al., 2021) (De Sá et al., 2015), including zooplankton (Cole et al., 2013) (Manríquez-Guzmán et al., 2023) (Malinowski et al., 2023), barnacles (Goldstein and Goodwin, 2013), bivalves such as mussels and oysters (Romdhani et al., 2022) (Cole and Galloway, 2015), as well as bigger organisms like pelagic fish (Lusher et al., 2013) and whales (Besseling et al., 2014) (Lusher et al., 2015b), ingestion is considered the main route of exposure to MPs. This widespread ingestion highlights the profound effect that MPs have on marine life. By finding different polymer particles in the gastrointestinal system and in the tissues of marine species, including fish (Pappoe et al., 2022), sea worms (Missawi et al., 2020), mussels (Romdhani et al., 2022) (González-Soto et al., 2019) (Romdhani et al., 2024), and seabirds (Fackelmann et al., 2023), the ingestion of MPs has been confirmed. According to (Santos et al., 2021), 1,288 marine species have been found to consume plastics. Approximately 400 species of fish, 54% of which are commercially relevant, ingest MPs ranging in size from 1μm to 5 mm (Djekoun et al., 2024) (Savoca et al., 2021). Furthermore, it has been reported that at least fifty cetaceans' species (56% of the infraorder) have consumed marine litter (Fossi et al., 2018) (Pereira et al., 2023). MPs have also been detected in various shellfish species, raising concerns about human health implications through dietary exposure (Li J. et al., 2021). They have been found in diverse

TABLE 2 Effects of plastics on marine organisms following a trophic gradient from primary producers to the top of the trophic chain. The following abbreviations were used: PVC: Polyvinyl chloride; PE: Polyethylene; LDPE: Low-Density Polyethylene; HDPE: High-Density Polyethylene; PP: Polypropylene; PA: Polyamide; PAC: Polyacetylene; PS: Polystyrene; UPVC Unplasticized polyvinylchloride; PMMA: Polymethylmethacrylate; PET: Polyethylene-terephtalate; PBAT: Polybutylene Adipate Terephthalate; BPA: Bisphenol A.

Target organisms	Plastic particles concentration	Plastic particles type/size	Effects	References
Cyanobacteria				
Microcystis aeruginosa	10–100 mg L^{-1}	PA, PE and PVC	Impairing Chlorophyll-*a*, photosynthetic activity, and growth rate	Kiki et al. (2023)
Limnospira (Arthrospira) maxima	5–80 mg L^{-1}	PET (4.7µm ± 0.5 µm)	Cell damage and an increase in carbon and nitrogen content	Pencik et al. (2023)
Algae				
Chlorella vulgaris	10–100 mg L^{-1}	PA, PVC and PE	Impairing Chlorophyll-*a*, photosynthetic activity and growth rate	Kiki et al. (2023)
	5–80 mg L^{-1}	PET (4.7 µm ± 0.5 µm)	Cell damage, changes in chlorophyll *a* composition and inhibitory effect on growth	Pencik et al. (2023)
Chlamydomonas reinhardtii	5–80 mg L^{-1}	PET (4.7 µm ± 0.5 µm)	Cell damage, changes in chlorophyll *a* composition and inhibitory effect on growth	Pencik et al. (2023)
Chlorella sp.	1.8–6.5 mg L^{-1}	PS beads (20 nm and 2.5 × 10^6 cm^2/g)	Decrease in photosynthetic activity	Bhattacharya et al. (2010)
Skeletonema costatum	50 mg L^{-1}	PVC (average diameter 1 µm)	Inhibition of maximum growth ratio (IR) Negative effects on algal photosynthesis (chlorophyll content and photosynthetic efficiency (ΦPSII)	Zhang et al. (2017)
Microalgae		MPs < 5 mm	Inhibition of growth, decrease in nutritional availability, decrease in chlorophyll and photosynthesis activity. Induction of oxidative stress, changes in morphology, reduction and promotion of hetero aggregates	Prata et al. (2019)
Phytoplankton		High MPs concentration	Significant changes in the phytoplankton community structure	Hitchcock (2022)
Scenedesmus obliquus	1 g L^{-1}	PS beads (70 nm)	Reduction of population growth and chlorophyll concentrations	Besseling et al. (2014)
Thalassiosira pseudonana (CCMP 1335) *Skeletonema grethae* (CCMP775) *Phaeodactylum tricornutum* (UTEX646) *Dunaliella tertiolecta* (UTEX999)	0–250 mg L^{-1}	PS NPs- and MPs (55 nm nanoparticles; 1 and 6 µm microparticles)	Inhibition of growth and induced production of exopolymeric substances with high protein-to-carbohydrate ratios	Shiu et al. (2020)
Cnidarians/Corals				
P. cf. damicornis	2.28 ± 0.12 particles g^{-1}	Nylon, PAC (101–200 µm)	Shift the coral-reef community assemblages and affect resilience	Jandang et al. (2024)
P. lutea	1.58 ± 0.25 particles g^{-1}			
Lobophyllia sp.	0.70 ± 0.12 particles g^{-1}			
P. sinensis	1.12 ± 0.25 particles g^{-1}			
Lophelia pertusa	350 spheres L^{-1}	PE beads (500 µm)	Reduction of skeletal growth rates and of septal growth	Mouchi et al. (2019) Chapron et al. (2018)
Pseudodiploria clivosa	10 mg L^{-1} per size class	PE (212–250 µm, 425–500 µm, and 850–1,000 µm)	Reduction in growth rate, impaired skeletal calcification, reduction in tissue surface area	Hankins et al. (2021)
Acropora cervicornis				

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TABLE 2 (*Continued*) Effects of plastics on marine organisms following a trophic gradient from primary producers to the top of the trophic chain. The following abbreviations were used: PVC: Polyvinyl chloride; PE: Polyethylene; LDPE: Low-Density Polyethylene; HDPE: High-Density Polyethylene; PP: Polypropylene; PA: Polyamide; PAC: Polyacetylene; PS: Polystyrene; UPVC Unplasticized polyvinylchloride; PMMA: Polymethylmethacrylate; PET: Polyethylene-terephtalate; PBAT: Polybutylene Adipate Terephthalate; BPA: Bisphenol A.

Target organisms	Plastic particles concentration	Plastic particles type/size	Effects	References
Crustacea				
Eurytemora affinis	300 μg L^{-1}	LDPE, PBAT (1–10 μm [Az1])	Dysbiosis of gut microbiota	Thery et al. (2023)
Artemia parthenogenetica	100 mg L^{-1} (1.10 and 1.26 10^6 items m^{-3})	PE, PS	Diversity increases and dysbiosis of gut microbiota, and reduction of the growth rate [Az2]	Li et al. (2021c)
Litopenaeus vannamei	10 and 20 mg mL^{-1}	PS (75 nm)	Reduction in intestinal fold height, intestinal structural damage, dysbiosis of gut microbiota, oxidative stress and metabolic disorders	Zhu et al. (2024)
Zooplankton				
Centropages typicus	>4,000 mL^{-1}	PS beads (7.3 μm)	Decrease in algal ingestion rate	Cole et al. (2013)
Acartia clausi		PS beads (15.7 μm ESD)	Decrease in algal ingestion rate	Ayukai (1987)
Calanus pacificus		PS beads (15 μm)	Decrease in algal ingestion rate	Fernández (1979)
Daphnia magna	0.22–103 mg nano-PS L^{-1}	Nano-PS aged, Pristine nano-PS	Reduction of body size and severe alterations in reproduction and neonatal malformations	Besseling et al. (2014)
Calanus helgolandicus	75 mL^{-1}	PS beads (20 μm)	Decrease in ingestion, fecundity and survival	Cole et al. (2015)
Bivalves				
Cerastoderma glaucum and *Limecola balthica*	0.1% and 0.5% sediment dwt	PE microspheres (63–75 μm, 150–180 μm and 250–300 μm)	Decrease in emergence frequency of near-surface-dwelling	Urban-Malinga et al. (2021)
Crassostrea gigas	0.023 mg L^{-1}	PS microspheres (2 and 6 μm)	Decrease in sperm motility, oocyte numbers (fecundity) and size (energetic investment per oocyte), larval yield and growth	Sussarellu et al. (2016)
Mytilus galloprovincialis		PE	Genotoxicity, tissue damage of gills and Digestive system	Bråte et al. (2018)
Mytilus edulis	0.2 mg L^{-1} (~1,170 MPs mL^{-1}) and 20 mg L^{-1} (~117,000 MP mL^{-1})	HDPE (4–6 μm and 20–25 μm)	Alteration of gut microbiota and an increase in the abundance of potential human pathogens	Li et al. (2020b)
Worms				
Arenicola marina	0%–5% by weight (sediment)	UPVC (130 μm)	Decrease in feeding activity and energy reserves and increase of phagocytic activity of immune cells	Wright et al. (2013)
Hediste diversicolor	10 and 50 mg kg^{-1} sediment	MPs (<30 μm)	Increase of acidic mucus production in seaworm tissues	Abouda et al. (2024)
Namalycastis jaya		PS MPs	DNA and oxidative damages	Saikumar et al. (2024)
Sea Urchins				
Paracentrotus lividus		PE, PP	Impaired feeding, reduced reproductive success, and physical damage to internal organs	Galloway et al. (2017)
Arbacia lixula	26 μg L^{-1}	PE MPs	Negative effects on physiology and histology. Decrease in the viabilities of coelomocyte subpopulations	Şahin et al. (2024)
Paracentrotus lividus	10, 50, 10^3, 10^4 L^{-1}	PS microbeads	Affecting immune cell proteome in a concentration-dependent response, alterations in minor morphological immune cell types, severe alterations of metabolism and cellular processes	Murano et al. (2023)

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TABLE 2 (*Continued*) Effects of plastics on marine organisms following a trophic gradient from primary producers to the top of the trophic chain. The following abbreviations were used: PVC: Polyvinyl chloride; PE: Polyethylene; LDPE: Low-Density Polyethylene; HDPE: High-Density Polyethylene; PP: Polypropylene; PA: Polyamide; PAC: Polyacetylene; PS: Polystyrene; UPVC Unplasticized polyvinylchloride; PMMA: Polymethylmethacrylate; PET: Polyethylene-terephtalate; PBAT: Polybutylene Adipate Terephthalate; BPA: Bisphenol A.

Target organisms	Plastic particles concentration	Plastic particles type/size	Effects	References
		Fish		
Dicentrarchus labrax		PMMA (45 nm), PVC	Decrease in esterase and alkaline phosphatases levels in blood plasma and skin mucus respectively. Increase expression of genes and receptors involved in lipid metabolism. Severe histological changes in distal intestine	(Brandts et al., 2018) (Pedà et al., 2016)
Danio rerio (zebrafish)	100 and 1,000 μg L^{-1}	PS, PP (≤12 μm)	Decrease in larvae swimming competence, survival and hatching rates. Upregulation of inflammation and oxidative stress related genes and inhibition or increasing of acetylcholinesterase activity. Apoptosis in blood cells and liver oxidative damage	(Pedà et al., 2016) (Santos et al., 2021) (Priyadharshini et al., 2024)
Oryzias melastigma	10 mg L^{-1}	PS (2 μm, 10 μm, 200 μm)	Diversity alteration and dysbiosis of gut microbiota, hepatic inflammation and little fibrosis, and lipid metabolic disorders	Zhang et al. (2021b)
Oryzias javanicus	100, 500 and 1,000 μg L^{-1}	PS (0.5 μm)	Decrease in gut microbial richness and diversity and metabolic disorder	Usman et al. (2022)
Oryzias latipes	0.1 mg L^{-1} (2.5 10^7 particles L^{-1})	PS (2 μm)	Dysbiosis of gut microbiota, reduction of the functional bacterial species, reduction of the shoaling behavior	Tamura et al. (2024)
		Marine Mammals		
Marine mammals		65.5–436 μm in the acoustic fat pads	Inhibition of acoustic fat pads critical functions	Merrill et al. (2023)
Marine mammals		24.4–1,387 μm in Blubber tissue	Inhibition of blubber critical functions	Merrill et al. (2023)
Balaenoptera musculus (Blue whale)		PE, PP (1 mm to several cm)	Digestive blockages, exposure to toxins, and impact on prey species	Desforges et al. (2015)
		Sea Turtles		
Chelonia mydas		PE, PP (1 mm to several cm)	Digestive blockages, malnutrition, decrease in growth rates, and increase of mortality	Wright et al. (2013)
Caretta caretta		BPA, PTA, PET and PC in abdominal fat and liver tissues (0.45 μm - 1 mm)	Gastrointestinal impairment and an important level of contamination in tissues	Di Renzo et al. (2021)
		Seabirds		
Fulmarus glacialis		PE, PP (1 mm to several cm)	False sense of satiation, malnutrition, physical injury, and exposure to toxic chemicals	Galloway et al. (2017)
Ardenna carneipes		MPs and MAPs	Extensive scar tissue formation, fibrosis in seabird stomach tissues, *"Plasticosis"*	Charlton-Howard et al. (2023)
Calonectris borealis	0–57 pieces, 0–0.1016 g	MPs	Alteration of the composition of the gastrointestinal tract (GIT) and increase in microbial diversity	Fackelmann et al. (2023)
Fulmarus glacialis	0–57 pieces, 0–0.1016 g	MPs	Decrease in commensal microbiota, and increase in pathogens and antibiotic-resistant and plastic-degrading microbes of the GIT	Fackelmann et al. (2023)

bivalve species (Djekoun et al., 2024) (Cho et al., 2019) (Hermabessiere et al., 2019) (Baechler et al., 2020) (Aung et al., 2022), such as mussels, especially *Mytilus edulis*.; and the common cockle *Cerastoderma edule* (Hermabessiere et al., 2019) (Botelho et al., 2023). Moreover, MPs have been found in farmed oyster shells (*Crassostrea angulata*) off Taiwan's coast; the quantities were higher in smaller shells where inorganic fractions containing fibrous MPs and rayon were predominant (Chen et al., 2023).

Small plastic fragments may have distinct effects due to their increased surface area, their ability to cross tissue or cell boundaries, or their interactions with other chemicals present in the environment (Worm et al., 2017). The small size of MPs promotes their translocation across gastrointestinal membranes via endocytosis-type mechanisms and their distribution in tissues and organs (Alimba and Faggio, 2019). The presence of MPs outside the gastrointestinal tracts of marine mammals (dolphin, gray whale, bearded seal) was first revealed by Merrill et al. (2023), marking the first identification of translocation and deposition of MPs into various tissues including blubber, melon, acoustic mandibular jaw fat, and caudal lung. This research indicated negative impacts on these tissues, potentially inhibiting critical functions or contributing to the cumulative effects of multiple anthropogenic stressors on marine mammals, ultimately reducing their fitness (Pirotta et al., 2022).

Microplastics have physical effects, on aquatic organisms mainly through mechanisms such as entanglement, suffocation and ingestion (Pegado et al., 2018), with ingestion and entanglement can lead to death, reduced growth rate, reproductive complications and hepatitis (Auta et al., 2017). On the other hand, according to Alimba and Faggio (2019), MPs increase the disruption of the gene expression necessary for controlling oxidative stress in marine vertebrates and invertebrates, leading to genomic instability, endocrine disruption, neurotoxicity, reproductive abnormalities, embryotoxicity and transgenerational toxicity (Romdhani et al., 2022) (Romdhani et al., 2024) (Missawi et al., 2022). Reproduction is particularly sensitive, with energy depletion resulting from exposure to MPs affecting fecundity and fertility (Sussarellu et al., 2016). Moreover, NPs and MPs have been reported to interfere with feeding and reproduction, negatively impacting fertility and offspring quality, which are key components of an organism's fitness (Romdhani et al., 2024) (Worm et al., 2017). For the Zebrafish, sentinel species in MPs research, the exposure to different types of MPs leads to several effects including disruption of metabolism, chronic inflammation, intestinal toxicity and damage to the intestinal lining and structure, decreased reproductive ability, and possible effects on growth and development (Marana et al., 2022) (Qiao et al., 2019a) (Jin et al., 2017). Hepatic cellular damage partly due to the downregulation of genes and pathways linked to DNA damage repair and cell proliferation regulation has also been reported (Tian et al., 2024).

Concerns have been expressed over MPs' effects on marine fauna's gut microbiota because it is essential to metabolic regulation in all organisms and coordinates most metabolic pathways. Several marine organisms, such as mollusks (Li L-L. et al., 2020), crustaceans (Li Q. et al., 2021) (Thery et al., 2023) (Zhu et al., 2024), fish (Zhang C. et al., 2021) (Usman et al., 2022) (Tamura et al., 2024), and seabirds (Fackelmann et al., 2023), can develop dysbiosis, or an imbalance of microbial species, in their gut microbiota as a result of MP exposure. In general, the relative abundance of the main bacterial groups—Proteobacteria, Firmicutes, Bacteroidetes, Actinobacteria, and Fusobacteria—increases (Fackelmann et al., 2023) (Zhu et al., 2024) (Li Q. et al., 2021) (Pamanji et al., 2024) or decreases (Zhang C. et al., 2021) (Li J. et al., 2021) (Zhu et al., 2024). Furthermore, marine taxa exposed to MPs exhibited alterations in the composition of their gut microbiota, with a decline in the abundance of beneficial and commensal bacteria such as Sulfitobacter and Pseudoalteromonas genera (Zhu et al., 2024) and an increase in opportunistic and potentially pathogenic bacteria like *Pseudomonas*, *Aeromonas*, *Streptococcus* (Usman et al., 2022) and *vibrio* (Tamura et al., 2024) (Zhu et al., 2024), as well as antibiotic-resistant and plastic-degrading microbes. Some fish and shrimp studies also report a reduction in gut microbial richness and diversity (Zhang C. et al., 2021) (Usman et al., 2022). However, an increase in gut microbial diversity and richness has been observed in the Brine Shrimp *Artemia parthenogenetica* and the Zebrafish *Danio rerio* (Li R. et al., 2023) (Tian et al., 2024), respectively, indicating that the response may differ by species. In addition, the extent of gut microbiota shifts depends on the exposure duration (Li L-L. et al., 2020) well as on plastic size (Zhang C. et al., 2021), type and concentrations (Thery et al., 2023), even though the concentrations used in the experimental studies can be realistic, much like those in the environment, or nonreal, much lower or higher.

Microplastic-induced dysbiosis has been associated with negative health effects, including lower growth (Li Q. et al., 2021), oxidative stress (Zhu et al., 2024) (Pamanji et al., 2024), hepatic inflammation (Zhang C. et al., 2021) and dysfunction (Tian et al., 2024), intestine structural damage (Zhu et al., 2024), and reduced shoaling behavior (Tamura et al., 2024). Dysbiosis may also disrupt the host metabolic homeostasis contributing then to the development of metabolic disorders (Zhang C. et al., 2021) (Usman et al., 2022), including an alteration of metabolic markers such as lipid, glucose, and of phospholipid metabolism since certain bacteria were linked to phospholipids (Qiao et al., 2019b).

Moreover, since many marine species are consumed by humans, the enrichment of potential pathogens in the gut may increase the organism's susceptibility to infections or diseases, as well as have an impact on food safety and the health of marine ecosystems.

Despite all the reported alterations at cellular level reflecting crucial toxicity that can be extended to enable concluding about species populations decline and even possible risk of extinction, information on how NPs and MPs can enter living cells and thus provoke the damaging effects is very controversial. This is even more challenging when dealing with biological barriers such as brain and reproductive organs. Moreover, MPs have been reported and their effects assessed at different levels of the marine trophic chain from phytoplankton to top level organisms like cetaceans (Table 2), however and to our knowledge no experiments have been attempted to assess its trophic transfer rate throughout the entire marine food chain.

4.2 Microbial communities

Recent research has focused on the effects of different types of MPs on marine microbial communities, that are attached to MP particles or free-living, using advanced methods such as high-throughput sequencing of 16S and 18S rRNA gene, gene expression analysis, and molecular techniques. This has helped to clarify the wider ecological and health implications of MPs pollution by examining how MPs influence the composition, diversity, and function of these communities. MPs can be rapidly colonized by diverse organisms through biofouling processes (Carson et al., 2013) (Reisser et al., 2014) leading to diverse biofilm communities adapted to plastics as a colonization surface. Microplastics that act as an artificial microbial reef, have synergetic effects on the development, transportation, persistence, and ecology of these communities (Dey et al., 2022). Investigations into the plastisphere, the microbial communities that colonize and live on the surface of floating plastic debris in aquatic environments (Zettler et al., 2013), have revealed that it hosts a wide range of microorganisms including archaea, bacteria, eukaryotes (fungi, algae, protozoa, and even tiny invertebrates), and even viruses (Lacerda et al., 2022). Eukaryotic organisms colonizing marine MPs are particularly more benthic eukaryotes than the free-water community, notably diatoms which are early and/or dominant colonizers (Eich et al., 2015) (Zhao et al., 2021) (Davidov et al., 2024). Bacteria were seemingly the most abundant biofilm members (Dey et al., 2022), with Proteobacteria (particularly alpha- and Gamma-proteobacteria) being the most identified on marine plastics from different seas and oceans and at different depths (sea surface, seafloor, etc.). Bacteroidetes, Actinobacteria and Cyanobacteria are also common groups of plastisphere community (Bryant et al., 2016) (Dussud et al., 2018) (Harvey et al., 2020) (Chen et al., 2021), (Dey et al., 2022) (Lacerda et al., 2024). Among Proteobacteria, the two hydrocarbonoclastic orders, Oceanospirillales and Alteromonadales, are consistently the more abundant, potentially biodegrading plastisphere members (Wright et al., 2021). In addition, Photobacterium, Pseudoalteromonas, and Psychrobacter, are the dominant Proteobacteria genera that are known for their ability to biodegrade and utilize plastics as a source of carbon and nutrients (Raghul et al., 2014) (Muriel-Millán et al., 2021) (Atanasova et al., 2021). The plastic debris was also found to host taxa that play significant roles in biogeochemical cycles (e.g., cyanobacteria, Erythrobacter) and hygienically relevant bacteria (e.g., Chryseobacterium, Brevundimonas) (Koh et al., 2023). These studies emphasize the metabolic activity of plastisphere microorganisms and their potential impact on the global ecosystem functions.

Bacterial communities colonizing marine plastics are characterized by high diversity and they include pathogens for animals (Priyadharshini et al., 2024) (Radisic et al., 2020) and humans (Kirstein et al., 2016) (Rodrigues et al., 2019) (Silva et al., 2019) (Wu et al., 2019) such as *Vibrio* spp., *E. coli* (Lacerda et al., 2024) (Bowley et al., 2021), *Enterococcus faecalis* (Lear et al., 2021) and bacteria resistant to antimicrobials (Sababadichetty et al., 2024), which constitutes potential risks to health. Furthermore, studies using high throughput sequencing have demonstrated within the genomes of plastic biofilm isolates, the presence of a wide variety of antimicrobial resistance genes, including a diversity of multi-drug efflux pumps and beta-lactams (Sababadichetty et al., 2024) (Rasool et al., 2021) (Lear et al., 2022). This makes MPs a vector of pathogens as well as support for horizontal gene transfer, therefore enhancing the spread of antibiotics gene resistance which constitutes a threat for human and marine organisms' health. Furthermore, the White Spot Syndrome Virus (WSSV), a shrimp pathogen, was recently found on seawater plastics biofilm, highlighting the plastisphere's potential as a disease vector in the marine environment and its ecological and economic impacts (Lacerda et al., 2024). The plastisphere often hosts communities and or taxa that differ from that of the surrounding environments including seawater, sediment and sand beaches (Sababadichetty et al., 2024) (Amaral-Zettler et al., 2020) (Harrison et al., 2014) (Lobelle and Cunliffe, 2011), (Battulga et al., 2024) (Sun et al., 2024). Diversity, richness and taxonomic composition of plastisphere community may differ depending on several factors including environment, abiotic parameters and plastic type and morphotype. Differences in the bacterial community composition at various taxonomic levels were detected depending on the plastic type, i.e., PS *versus* PE and PP (Frère et al., 2018) and wild plastic PE *versus* PP and PS (Vaksmaa et al., 2021). An absence of changes was however found among five household plastics (LDPE), (HDPE), (PP), (PVC) and (PET) (Lear et al., 2022), as well as between seawater-collected plastics (Lacerda et al., 2024). Depending on the morphotypes of MPs (fiber, film, foam, and fragment), no significant differences in Bacterial and fungal communities' composition were found (Battulga et al., 2024). Furthermore, eukaryotic communities can be significantly influenced by plastic polymer type and time incubated. (Guo et al., 2022).

In summary, variations in MPs samples origins (geographical location, depth, sediment vs. water column, etc.), abiotic parameters, plastic types and morphotypes, and methodology all contribute to the reported variations in the taxonomic composition of plastisphere microbial communities. Future research should focus on how the native microbiota, the microorganisms already present in the environment, and the MPs features such as morphotypes, polymers, etc., could individually contribute to the structuring of the plastisphere communities.

5 Impacts on marine ecosystem services (MESs) and blue carbon ecosystems (BCEs)

Microplastics have emerged as a significant environmental contaminant with wide-reaching impacts on MESs as shown in Table 3. They present a complex threat to marine ecosystems by interfering with MESs and compromising overall marine health, which in turn affects the essential services these ecosystems offer to both humans and environment. These services include provisioning, regulating, supporting, and cultural services that humans derive from marine ecosystems. Considering the value of marine services to society, estimated at USD 49.7 trillion per year, the presence of marine plastic debris results in an annual loss of USD 0.5–2.5 trillion, with a yearly cost in terms of reduced marine natural capital ranging from USD 3,300 to USD 33,000 per ton of plastic (Beaumont et al., 2019).

5.1 Impacts on provisioning services: Fisheries and aquaculture

Provisioning services in marine environments refer to the goods that humans directly obtain from the sea, primarily food resources like fish and shellfish. Plastic pollution significantly impacts these services in various ways including contamination of seafood, health risks to humans, and economic impacts on fisheries and aquaculture leading to restricted catches due to litter in nets. For instance, 86% of Scottish fishing vessels have been impacted by plastic pollution, which damages fishing gear, reduces catch quality, and increases operating costs. This pollution costs these fleets an estimated USD 12.8–14.2 million per year, representing about 5% of the total revenue of the affected fisheries. This financial burden

TABLE 3 Impacts of MPs on marine ecosystems services (MESs).

Type of MESs	Sub-type	Impact	Description	References
Regulating services	Climate Regulation	The photosynthetic system of microalgae	Decrease of chlorophyll content and photosynthetic efficiency (ΦPSII). (*Skeletonema costatum*)	Zhang et al. (2017)
			Decrease of chlorophyll-*a* content (*Chlorella vulgaris*)	Tunali et al. (2020)
		Promotion of CH_4 and CO_2	Degradation of plastic materials induces increase in CH_4 and CO_2 emissions	Kida et al. (2023)
		Carbon input	Decrease of carbon input by inhibiting fecal deposition	Wieczorek et al. (2019)
		CO_2 emission	Inhibition of carbon ingestion by plankton	Shen et al. (2020)
			Inhibition of growth and reproduction of plankton	Liu et al. (2020)
			Inhibition of plant growth by affecting photosynthesis	Sjollema et al. (2016)
			Penetration of microalgae cell walls to inhibit CO_2 uptake	Bhattacharya et al. (2010)
	Nutrients cycle	Nitrogen input	Reduction of nitrogen input by inhibiting urease activity	Wieczorek et al. (2019)
		NH_3 input	Ammonification by inhibiting urease activity	Yu et al. (2021a)
		Phosphorus input	Reduction of soil total phosphorus content	Yu et al. (2021a)
	Water purification	Reduction in filtration capacity	Clogging and damage of filtration systems	(Li et al., 2021a) (Ding et al., 2020)
Provisioning services	Fisheries	Ecotoxicological impacts	Disruption in tissues, organs, intestinal permeability, intestinal inflammation, disorders of the intestinal microbiome, neurological functions, immune dysfunction, metabolism and brain	(Qiao et al., 2019b) (Ding et al., 2020) (Jacob et al., 2020) (Gu et al., 2020)
	Aquaculture	Reduction of efficiency and productivity	Water acidification	Gewert et al. (2015)
			Impacts on ecological balance of aquaculture environment	Zhang et al. (2022)
			Ingestion of toxins by aquaculture products	(Cai et al., 2017) (Rummel et al., 2017)
			Increase the abundance of antibiotic resistance genes in aquaculture environments and increase potential risks of losing effectiveness for antibiotics	Lu et al. (2019)
			Loading many viruses	Li et al. (2022b)
Supporting services	Habitat provision and biodiversity	Habitat alteration and loss of biodiversity	Disruption of benthic communities	Khalid et al. (2021)
			Menace nesting sea turtles	Nelms et al. (2016)
			Disruption of the wellbeing and longevity of coral reef ecosystems	Rahman et al. (2023)
			Decline of Seagrass beds	Li et al. (2023b)
			Creation of artificial habitats: plastisphere	Reisser et al. (2014)
	Invasive species spread	Ecological imbalance and displacement of native species	Promotion of colonization of various harmful algal blooms	(Zettler et al., 2013) (Masó et al., 2003) (Masó et al., 2016)
			Transport of exotic pathogenic bacterium	(Zettler et al., 2013) (Kirstein et al., 2016) (Viršek et al., 2017)
			Transport of pathogenic *vibrio* species	Rummel et al. (2017)
			Transport of hydroids, bryozoans, barnacles, mollusks, and Polychaeta worms	(Masó et al., 2016) (Yang et al., 2020)
Cultural services	Tourism/Recreation and Heritage	Physical health	Physical injuries such as cuts due to sharp debris	Beaumont et al. (2019)
		Mental health	Disruption peoples' quality of life by reducing the aesthetic appeal of the marine environment	Beaumont et al. (2019)
		Heritage of communities and individuals	Degradation of natural learning environments	Beaumont et al. (2019)

10.3389/fenvs.2025.1635230

TABLE 4 Financial Impact of Microplastics on Marine Ecosystem Services (MESs) and Blue Carbon Ecosystems (BCEs). The estimated global value, the potential loss due to microplastics (MPs), and the corresponding estimation year are indicated for each service. The potential losses, expressed as a percentage of global GDP, are calculated by dividing the estimated potential loss of each ecosystem service by the global GDP for the respective estimation year indicted between brackets. The estimated global value is derived from data corresponding to the reference indicated by*.

Service type	Ecosystem service	Estimated global value USD/year	Potential loss due to MPs USD (year)	Potential loss as % of global GDP	References
Provisioning	Fisheries and aquaculture	~401* billion	~6–19 billion (2019)	0.006%–0.02%	(FAO. The State of World Fisheries and Aquaculture, 2020, 2020) (Raes et al., 2023)
Regulating	Nutrient Cycling	~13,000* billion	~650 billion (2019)	0.74%	(Costanza et al., 1997) * (Beaumont et al., 2019)
	Water Purification	~1700* billion	~100–200 billion (2019)	0.011%–0.22%	(Costanza et al., 1997) * (Beaumont et al., 2019)
	Climate Regulation	~200* billion	~2–20 billion (2019)	0.002%–0.02%	(Costanza et al., 1997) * (Beaumont et al., 2019)
Supporting	Habitat Provision	~1,000* billion	~100–300 billion (2019)	0.11%–0.34%	(Costanza et al., 1997) * (Beaumont et al., 2019)
	Biodiversity Maintenance	~3,000-5,000* billion	~300–900 billion (2019)	0.34%–1.02%	(Costanza et al., 1997) * (Beaumont et al., 2019)
	Invasive Species Transport	~120* billion	~10–50 billion (2019)	0.01%–0.05%	(Pimentel et al., 2005) * (Beaumont et al., 2019)
Cultural	Tourism, Recreation Education and Public pollution perception	~4,400 billion	~13–25 billion (2019)	0.01%–0.02%	Beaumont et al. (2019)
Blue Carbon Ecosystems	Coastal protection, carbon sequestration, water filtration and habitat provision	1,000-20000* USD/ha	>50 USD million (2011)	-	(Barbier et al., 2011) *

emphasizes how urgently sustainable waste management and pollution mitigation strategies are needed to protect marine resources and support sustainable coastal economies. Furthermore, the fishing industries faces challenges with derelict fishing gear, which can damage vessels, require the replacement of lost gear, and lead to potential catch losses, thereby reducing revenue (Arabi and Nahman, 2020). In 2002, a single trap fisher in the Scottish Clyde fishery faced losses of approximately USD 21,000 in fishing gear and USD 38,000 in lost fishing time (Macfadyen et al., 2009). MPs are found in various marine organisms including fish (Ferreira et al., 2018), bivalves (Bråte et al., 2018), cephalopods (Oliveira et al., 2020) or crustaceans (Botterell et al., 2019), entering the food chain and potentially affecting human health (Tuuri and Leterme, 2023). Fish, shellfish and other seafood that humans consume are often contaminated with MPs, leading to bioaccumulation and biomagnification of harmful chemicals (Li J. et al., 2021) (Ding et al., 2020) (Bhuyan, 2022) (Barboza et al., 2018) (Wright and Kelly, 2017). MPs impact freshwater and marine fish in several ways, including impairing their feeding ability (Wright and Kelly, 2017), causing nutritional and growth disorders (Lusher et al., 2017), and promoting behavioral changes (Liang et al., 2023). Additionally, when these fish are consumed, MPs become part of the human diet (Smith et al., 2018).

According to the International Union for Conservation of Nature (IUCN), marine plastic pollution could result in economic losses ranging from $6 billion to $19 billion annually across 87 coastal countries (Table 4). This estimate extends beyond the direct impacts on fisheries and aquaculture to include broader economic effects on coastal economies, such as degradation of ecosystem services and reduced export revenues (Raes et al., 2023). More precisely, Beaumont et al. (2019) estimated that plastic debris imposes an annual global loss of $1.3 billion USD on the fishing and aquaculture industries, specifically through reduced catch, gear damage, and clean-up costs. This estimate, which has a relatively high degree of certainty within this narrowly defined scope, is derived from an earlier assessment by UNEP (2014) based on a limited number of national case studies. However, it does not account for broader indirect impacts such as disruptions to supply chains, or wider ecosystem service degradation. While this figure highlights the sector-wide burden, framing these losses against national economies underscores their broader significance. In Norway, where fisheries and aquaculture accounted for 2.3% of mainland GDP in 2022, average vessel losses of USD 12 000 per year reflect ongoing financial strain in an industry contributing roughly six billion USD to the economy (Fish farming Expert) (Fishfarming Expert, 2025). In Fiji, 2019 losses of over 600,000 USD correspond to about 0.011% of the country's total GDP of 5.44 billion USD (World Bank, 2023a). Likewise, in Ecuador, annual losses of 8.4 million USD represent approximately 0.007% of its 118.84 billion USD GDP (World Bank, 2023) (World Bank, 2023b) and in Peru, 8.27 million USD in losses equate to around 0.003% of a 267.6 billion USD economy (World Bank, 2023c). Although these percentages may seem modest, they reveal that MPs pollution exerts a measurable drag even on national economic output, reinforcing the urgency of targeted mitigation and policy action.

The accumulation of MPs by various shellfish can lead to unique health and performance deterioration, such as toxicological implications, behavioral changes, and growth and reproductive problems (Li J. et al., 2021) (Ding et al., 2020) (Hossain et al., 2024). MPs have also been found in aquafarms, where fish and mollusks are cultured for human consumption (Zhang et al., 2020) (Rochman et al., 2015). Harmful additives and absorb pollutants released by MPs in aquaculture environments can cause toxicological effects, impact behavior, growth, and reproduction of aquaculture species, and ultimately reduce the economic benefits of aquaculture. MPs entering the human body through aquaculture products also pose potential health risks at multiple levels (Wu et al., 2023).

5.2 Impacts on regulating services: nutrient cycles, water purification and climate regulation

Microplastics have a profound and detrimental impact on marine regulating services, which are critical for maintaining the health and stability of marine ecosystems (Sridharan et al., 2021). These tiny plastic particles infiltrate marine environments and disrupt various ecological processes. Key regulating services, such as nutrient cycling, water purification, and climate regulation, are particularly affected by MPs pollution.

The economic repercussions of MPs pollution are stark. As reported in Table 4, the estimated global economic value of these services amounts to approximately USD 15 trillion per year (Costanza et al., 1997). However, MPs pollution leads to significant disruptions of these functions, resulting in estimated economic losses ranging from USD 752 to 870 billion annually. For instance, a 5% disruption in nutrient cycling could represent a loss of USD 650 billion/year, while impairments in water purification capacities could incur losses between USD 100 and 200 billion/year (Beaumont et al., 2019). Climate regulation services may also experience economic damages ranging from USD 2 to 20 billion/year under an assumed impact of 1%–10% (Beaumont et al., 2019). The potential loss as a percentage of global GDP was calculated by dividing the estimated potential loss of each ecosystem service by the global GDP in 2019 (~USD 87.55 trillion). Collectively, these losses amount to approximately 1% of global GDP, a substantial figure that reflects a significant economic impact on the global scale. (Table 4).

Nutrient cycling is significantly disrupted by MPs through the alteration of microbial dynamics and nutrient availability. MPs serve as surfaces for biofilm development, enabling microorganisms to thrive, which can shift nutrient transformations, particularly nitrogen and phosphorus cycling (Chen et al., 2020). Additionally, MPs adsorb nutrients and pollutants from surrounding waters, affecting their bioavailability, and potentially leading to imbalances in nutrient dynamics. When ingested by marine organisms, MPs disrupt food webs and influence community structures, impacting ecosystem functions related to nutrient cycling (Wang et al., 2022). Furthermore, their presence in sediments modifies the physical and chemical properties of the benthic environment, affecting nutrient release and utilization (Green et al., 2016). Collectively, these interactions highlight the complex and multifaceted role MPs in marine nutrient cycles, posing risks to marine ecosystem health.

Microplastics pose significant challenges to water purification processes in marine environments. As these small plastic particles are pervasive, they can interfere with the natural filtration mechanisms of marine ecosystems, such as wetlands and mangroves, which are crucial for improving water quality (Qian et al., 2021) (Adaro and Ronda, 2024). Filter-feeding organisms, which can filter up to 5 m^3 of water per day, become less efficient as MPs clog their systems leading to poorer water quality and decreased availability of clean habitats for other marine life (Li J. et al., 2021) (Ding et al., 2022). Microplastics also adsorb pollutants, including heavy metals and Persistent Organic Pollutants (POPs), which may be released back into the water column upon degradation, exacerbating contamination levels (Rafa et al., 2024). Due to their hydrophobicity and their relatively large surface area, MPs act as vectors of harmful pollutants, such POPs facilitating their transfer to organisms (Huang et al., 2021). These substances, many of which are endocrine disruptors, bioaccumulative and persistent, can modify the metabolic and reproductive parameters (Galloway et al., 2015) (Koelmans et al., 2016). Plastics not only have the capacity to transport toxic substances but also to increase them in the environment. Adsorption of these substances is enhanced by the presence of biofilm, which alters the hydrophobicity of the plastic particle's surfaces. Additionally, the aging of plastics in marine waters changes their surface morphology facilitating the absorption of metallic ions (Squadrone et al., 2022). Additionally, the presence of MPs hinders the growth of beneficial microorganisms that play vital roles in nutrient cycling and bioremediation, further impairing the ecosystem's ability to purify water. This disruption compromises the health of marine organisms and the integrity of coastal and oceanic ecosystems, highlighting the urgent need for effective management strategies to mitigate MPs pollution. Microplastics also affect climate regulation by altering key processes such as carbon cycling and marine ecosystem health (Li K. et al., 2024) (Galgani et al., 2023). They affect phytoplankton communities, which play a crucial role in carbon sequestration through photosynthesis, and can hinder the biological pump which represents the mechanism by which carbon dioxide is absorbed from the atmosphere and transported to deeper ocean layers (Shen et al., 2020). Additionally, MPs can contribute to the degradation of marine habitats, such as coral reefs and seagrass beds, which are vital for carbon storage. They also disrupt food webs, impacting species that contribute to carbon cycling and ecosystem resilience. As these ecosystems weaken, their ability to sequester carbon effectively diminishes, potentially exacerbating climate change effects (Li K. et al., 2024). Addressing MPs pollution is therefore essential for maintaining marine biodiversity but also for supporting climate regulation efforts.

5.3 Impacts on supporting services: habitat provision, biodiversity and invasive species transport

Microplastics profoundly affect marine supporting services, especially habitat provision, biodiversity, and the transport of invasive species. The economic losses associated with habitat degradation can be substantial, affecting tourism, fisheries, and coastal protection services. For example, the loss of coral reefs alone is estimated to cost global economies around $375 billion annually due to lost tourism, fisheries and protection against erosion and storm damage (Chatterjee and Sharma, 2019). In terms of habitat provision, 70% of MPs debris accumulates in marine environments, altering the physical and chemical characteristics of habitats such as beaches, seafloors, and coral reefs (Mouat et al., 2010). This can change the sediment's texture, reduce light penetration, and introduce harmful chemicals, making the habitat less suitable for native species. For biodiversity, MPs pose a dual threat (Beaumont et al., 2019). Physically, they can cause internal injuries or blockages in marine organisms that ingest them, while chemically, they can leach toxic substances or adsorb pollutants, leading to bioaccumulation and biomagnification within the food web (Mouat et al., 2010). These effects can reduce the survival and reproductive success of marine species, causing population declines and shifts in community structure.

Additionally, MPs facilitate the transport of invasive species (Naidoo et al., 2020). They serve as rafts for microorganisms, algae, and invertebrates, allowing these species to travel across oceans and colonize new areas. This can disrupt local ecosystems by introducing competitors, predators, or pathogens to which native species are not adapted to cope with, leading to reduced native biodiversity and altered ecosystem functions (Beaumont et al., 2019) (Carney and Eggert, 2019). Microplastics also pose risk to zooplankton, marine mammals, birds and fish, and can serve as vector for the dispersal of harmful microalgae such as *Alexandrium*, *Coolia* and *Ostreopsis* (Zettler et al., 2013) (Masó et al., 2003) (Masó et al., 2016). These harmful species produce a variety of marine biotoxins implicated in contamination events affecting filter or grazer-feeding animals and human poisoning, sometimes with lethal outcomes (Anderson et al., 2012) (Parsons et al., 2012) (Trainer et al., 2012).

Beyond these direct ecological impacts, MPs pollution also threatens the broader supporting services that underpin marine ecosystem functioning and productivity. As shown in Table 4, the global economic value of these services is estimated at USD 4.1 to 6.1 trillion per year (Costanza et al., 1997) (Pimentel et al., 2005). Microplastic pollution compromises these functions, resulting in considerable economic losses. For example, degradation of coastal habitats could result in losses of USD 100 to 300 billion/year, while erosion of biodiversity and ecosystem stability may cost between USD 300 and 900 billion/year (Beaumont et al., 2019). Additionally, increased costs related to the facilitation of invasive species transport via MPs are estimated between USD 10 and 50 billion/year (Beaumont et al., 2019). When reported as a percentage of global GDP, the losses represent between 0.5% and 1.4% of global GDP. These figures underscore the critical importance of supporting services and highlight the substantial economic impacts that persistent MPs pollution could have on the resilience and productivity of marine ecosystems. Overall, the pervasive presence of MPs in marine environments undermines habitat quality, threatens biodiversity, and enhances the spread of invasive species, posing substantial risks to marine ecosystem health, stability and resilience.

5.4 Impact on blue carbon ecosystems

Wetlands and marine ecosystems, including seagrass meadows, mangrove forests, estuaries, and salt marshes, serve as sites of MPs deposition (Yu H. et al., 2021) (Ogbuagu et al., 2022). These BCEs are increasingly impacted by MPs contamination (Garcés-Ordóñez et al., 2019) (Huang et al., 2020) (Pinheiro et al., 2022) (Yin et al., 2021). Microplastics can attach to plants and carry toxic chemical compounds (Tourinho et al., 2019) (Goss et al., 2018), which may be ingested by herbivores and subsequently enter the food web (Goss et al., 2018). Additionally, the presence of MPs can influence the physical, chemical and biological properties of sediments, providing new niches for microbial communities (Wright et al., 2020) (Su et al., 2022). Moreover, accumulated MPs can damage the delicate structures of seagrass meadows and mangrove forests and animals within these ecosystems, inhibiting their growth and reproductive capabilities (Li R. et al., 2020).

Blue Carbon Ecosystems, such as mangroves, seagrasses, and salt marshes, occupy a small portion of the global seafloor (less than 1%) but are highly efficient carbon sinks, responsible for up to 50% of the total carbon sequestration (Mcleod et al., 2011) (Duarte et al., 2013). These ecosystems play a vital role in both short-term and long-term carbon storage, making them far more efficient compared to terrestrial forests (Mcleod et al., 2011) (Pendleton et al., 2016). Mangroves, in particular, contribute to the global mean burial rate of approximately 24 Tg C per year (Breithaupt and Steinmuller, 2022). The accumulation of MPs in these ecosystems disrupts their efficiency as carbon sinks.

Microplastics reduce the carbon sequestration efficiency of BCEs through several interconnected mechanisms. They interface with the sinking of organic matter such as marine snow by increasing the buoyancy of particle aggregates. This slows their descent to the seafloor, reducing the amount of carbon that becomes permanently buried in sediment (Kiørboe, 2001). In addition, MPs negatively impact key blue carbon plants such as mangroves, seagrasses and salt marsh vegetation by causing oxidative stress, blocking light, or introducing toxic chemicals. These effects reduce primary productivity and biomass accumulation, thereby decreasing carbon capture at the ecosystem level (Microplastic Pollution in Marine Environment, 2021). Furthermore, MPs disturb the structure and function of sediment microbial communities that are essential for transforming and stabilizing organic carbon. They alter sediment porosity and oxygen levels, leading to enhanced microbial degradation of stored carbon and increased CO emissions (Seeley et al., 2020) (Microplastic Pollution in Marine Environment, 2021). Microplastics may also carry harmful pollutants or pathogens that further disrupt benthic ecosystems. Together, these effects significantly weaken the role of blue carbon ecosystems as long-term carbon sinks, threatening their contribution to global climate regulation and carbon neutrality goals.

From an economic perspective, if MPs reduce carbon sequestration by just 1%, the loss in carbon storage potential could lead to a significant financial impact. Indeed, at a conservative carbon price of $50 per ton, this reduction could result in an economic loss of approximately $12 million annually from mangroves alone (Zhou et al., 2023) (Bandh et al., 2023). Similar financial impacts are recorded in coral reef ecosystems, where coral degradation linked to plastic debris could result in losses of up to $35,000 per hectare per year in tourism and coastal protection services. When extrapolated across global reef systems, these losses may exceed several billion dollars annually (Spalding et al., 2017).

This highlights the dual threat posed by MPs pollution not only compromising marine ecosystem health but also contributing to economic losses linked to climate regulation services. In addition, BCEs provide essential services such as coastal protection, water filtration, and habitat for wildlife. The economic value of these services is estimated to be in the range of $1,000 to $20,000 per hectare per year, depending on the ecosystem type and location (Table 4). Microplastics pollution that degrades these services could result in substantial losses. For example, a 5% reduction in service value across one million hectares could lead to losses exceeding $50 million annually (Zhou et al., 2023) (Bandh et al., 2023) (Noman et al., 2024).

Therefore, the financial burden of restoring BCEs affected by MPs can also be significant. Restoration efforts can cost between $10,000 to $100,000 per hectare, depending on the ecosystem type and the degradation level. If MPs necessitate restoration across thousands of hectares, costs could escalate into the millions or even billions (Bandh et al., 2023) (Zhang et al., 2024).

5.5 Impacts on cultural services: tourism, recreation, education and public pollution perception

Many coastal communities derive cultural identity and livelihoods from their marine environment. The degradation of these ecosystems can lead to significant losses in cultural services, which might be valued at around USD 4.4 trillion per year (Table 4). Even a small degradation could represent millions in lost cultural heritage value (Chatterjee and Sharma, 2019). Marine plastic pollution has significant implications for the tourism industry, leading to decreased revenue and substantial economic costs related to cleaning and maintaining affected areas (Aminur Rahman et al., 2023). Thus, to prevent losses in tourism income and support sustainable coastal economies, some municipalities invest heavily in clean-up efforts to remove debris from beaches and public spaces. For instance, municipalities in Belgium, the Netherlands, and the UK spend between EUR 10–20 million annually on coastal debris removal to protect tourism (Rahman et al., 2023). Furthermore, the presence of MPs on beaches and in coastal waters also diminishes the aesthetic appeal and safety of these environments. Swimmers, divers, and beachgoers may encounter polluted waters and shores, reduce enjoyment and increase potential health risks from direct contact with MPs or associated toxins. In Bali, plastic pollution caused such a decline in tourist satisfaction that the local government declared a “trash emergency” in 2017. Cleanup costs surged to over $1 million per month, and tourism revenue dropped by nearly 10% during peak season due to bad publicity and reduced water quality (Jambeck et al., 2015). Similarly, in South Korea, a 1% increase in visible marine debris has been estimated to lead to a 1.29% drop in beach visits, while in the UK, polluted beaches may result in up to a 50% reduction in tourist numbers, directly affecting local revenues (Jang et al., 2014) (UNEP, 2016). This can lead to a decline in tourism, adversely affecting local economies that rely on marine-based recreational activities (Mouat et al., 2010) (Beaumont et al., 2019). In addition, as of 2021, 20 million people were engaged in subsistence fishing, and nearly 30 million worked in capture fisheries, with 90% of these individuals located in low- and lower-middle-income countries (Food and Agriculture Organization of the United Nations, 2024). Thus, recreational (sport) fishing has become an additional source of income for many communities in these regions (Zhao Q. et al., 2022) (Arlinghaus et al., 2019). While participation rates remain low in some areas, it is estimated that at least 220 million people worldwide engage in recreational fishing (Arlinghaus et al., 2019). Local governments spend considerable resources to maintain beach quality. For example, the United States spends over $500 million annually on beach cleanups, while the EU coastal states collectively invest over €630 million each year for similar purposes (Ten Brink et al., 2016). In Cape Town, the city spends approximately $2 million per year on beach cleaning to maintain its status as a tourist destination.

Public perceptions of plastic pollution and its impacts are strongly linked to pro-environmental behavior (Kumar et al., 2021). Awareness and concern about plastic pollution vary based on age and education level. Older individuals and those with lower educational attainment tend to place less emphasis on recycling as a means of tackling the plastic problem (Miguel et al., 2024). This highlights the critical role of education for sustainable development in promoting awareness and proactive engagement with environmental issues across diverse populations. By integrating sustainability principles into education systems and curricula, individuals, particularly engineers who can devise innovative solutions through their designs, can develop the knowledge and skills needed to address challenges like plastic pollution effectively (Nakad et al., 2024) (Nakad et al., 2025a) (Nakad et al., 2025b). As a result, plastic pollution has socio-cultural impacts that extend beyond direct, quantifiable effects, influencing aspect like lifestyle, mental health, and cultural heritage (Yose et al., 2023).

Environmental attitudes play a significant role in shaping consumers’ intentions to reduce plastic use, particularly in the food products sector (Siddiqui et al., 2023). This highlights the close relationship between consumer behavior, environmental awareness, and efforts to address plastic pollution. For instance, the transition to sustainable packaging in the food and beverage sector has been slow and inconsistent, with many companies focusing on collection and recycling rather than adopting systemic sustainable solutions (Phelan et al., 2022).

Consumers associate plastics with more than just environmental issues, and different types of consumer awareness regarding plastics use, particularly in packaging have been identified (Rhein and Schmid, 2020) first type, awareness of environmental pollution, reflects an understanding of the global plastic waste problem, especially in oceans, and supports environmental protection efforts. The second, awareness of excessive plastic use, highlights the overuse and often unnecessary plastic packaging, particularly for items like fruits and vegetables. Third, awareness of consumers’ influence recognizes the role of consumer behavior in encouraging companies towards more sustainable practices. Fourth, awareness of consumers’ powerlessness expresses the feeling among some consumers that, while change is theoretically possible, practical

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alternatives are limited. Finally, awareness of the need for using plastic recognizes plastic's hygienic benefits in daily life, despite its environmental drawbacks. These insights suggests that consumer perceptions and attitudes toward plastic are complex and multifaceted (Rhein and Schmid, 2020).

6 Regulation

The growing environmental crisis caused by plastic pollution requires robust national and international regulations to mitigate its impact. The establishment of international regulations will ensure sustainable standards for plastic production, usage and end of life management and promote a circular economy that minimizes waste and conserves resources. By addressing this issue, plastic pollution can be reduced worldwide and protect the environment for future generations.

6.1 International and national regulations

Many international regulations have been developed like the International Convention for the Prevention of Pollution from Ships (MARPOL Convention) which aims to minimize marine pollution in seas and oceans, including pollution caused by plastics. Annex V of the MARPOL Convention addresses the prevention of pollution by garbage, such as plastics (MARPOL, 1973). Furthermore, the Basel convention aims to control the transboundary movements of hazardous waste, including plastic waste, ensuring its environmentally sound management to protect human health convention, and the environment (Rummel-Bulska, 2004). Additionally, Food and Drug Administration (FDA) regulations govern the safety of plastics used in food packaging, ensuring they do not pose health risks and encouraging recycling and proper disposal practices (FDA, 2020).

The international regulatory control system for waste transfers was created under the 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. Starting in 2019, parties to the Basel Convention adopted an alteration targeting plastic waste to protect human and environmental health from the negative impacts of the global plastic waste trade. The new regulations can significantly change the global plastic waste trade, affecting both Basel parties and non-party trading partners like the United States (Khan, 2020).

In Africa, most countries have implemented a total ban on the production and use of plastic bags, with 25 countries having announced such regulations. However, more than half of these regulations were enforced after 2014 (Ncube et al., 2021).

In Europe, regulations governing materials and articles made of plastic are outlined in Regulation No. 10/2011 (EU 2011c). This regulation is recognized as the Plastic Implementation Measure (Steensgaard et al., 2017). According to this regulation, plastics refer to all polymers that form the primary structural component of final materials, produced through processes like polymerization, polycondensation, or polyaddition. However, ion exchange resins, rubber, and silicones are not covered under the plastics regulation. Regarding recycled plastic materials for food packaging, an appropriate quality assurance system must be employed to ensure the recycled plastic meets the specifications detailed in the authorization, as specified in Regulation (EC) No. 2023/2006 Annex. In addition, The quality of the plastic input must also comply with Article three of Regulation (EC) No. 1935/2004 (Thapliyal et al., 2024). Another regulation developed by the European Union is the Directive (EU) 2019/904 on Single-Use Plastics. This directive aims to decrease the volume and environmental impact of specific plastic products, and to mitigate the adverse effects of certain plastic items on the environment, particularly aquatic ecosystems and human health (Thapliyal et al., 2024).

In the United States, in 2021, the FDA issued the guidance document "Use of Recycled Plastics in Food Packaging: Chemistry Considerations" to help food packaging manufacturers assess the processes for integrating post-consumer recycled plastic into food packaging. The FDA states that exposure to contaminants from recycled food contact materials at levels of 1.5 μg per person per day (0.5 ppb DC) or lower is generally considered safe (FDA, 2020). On the other hand, some countries have detailed regulations and standards for recycled plastic content in food packaging, while others offer general guidance or lack specific regulations altogether. The requirements for testing and certification differ from one country to another. Different countries have established national regulations for plastic materials to reduce pollution and manage waste more effectively (Table 5).

The regulatory framework addressing MPs pollution in the marine environment focuses on mitigating their presence by restricting the use of intentionally added MPs in products and addressing unintentional releases. This includes developing standardization, certification, and regulatory measures, as well as harmonizing methods for accurately measuring MPs releases.

The regulation is mainly aimed at primary measures for controlling the original types of MPs justified by the fact that marine MPs pollution is a phenomenon caused by specific pollutants rather than a specific behavior regulated by law. The primary MPs are microscopic polymers, mostly including microbeads. Therefore, the legislation mainly focuses on prohibiting the addition of microbeads to related products and prohibiting the sales, import, and export of such products (Li, 2022). However, to our knowledge, there are no regulations related to threshold levels of MPs in the marine environment and its related resources.

Some directives emerged relative to the monitoring aspects of MPs in the marine environment such as the Marine Strategy Framework Directive MSFD (MSFD, 2008/56/EC); which provides framework for monitoring and large-scale actions to assess and mitigate the impacts of marine litter in the European region. The background of this initiative stems from the fact that, while well-established methods exist for assessing litter on beaches, in the water column and on the seafloor, there remains a need to implement monitoring schemes specifically for MPs in sediments and invertebrates. Some actions have been identified to ensure the effectiveness of monitoring efforts including the identification of accumulation areas and sources of specific types of litter; enhance monitoring of riverine and atmospheric inputs of litters including MPs, take care of accidental inputs during extreme weather events (Galgani et al., 2024).

TABLE 5 National regulations on plastic materials in different countries.

Country	Regulations	References
India	Plastic Waste Management (Amendment) Rules (2021)	Ashish (2021)
California	SB 54: Plastic Pollution Prevention and Packaging Producer Responsibility Ac	Senate Bill (2022)
Australia	The National Plastic Plan 2021	Thapliyal et al. (2024)
Japan	The Plastic Resource Circulation Act (Act No. 60 of 2021	Ministry of the Environment and Japan (2021)
United Kingdom (UK)	The Plastic Packaging Tax (2022)	GOV. UK (2022)
China	GB/T 38,082–2019 Biodegradable Plastic Bags	Thapliyal et al. (2024)
United States	Use of Recycled Plastics in Food Packaging: Chemistry Considerations	Food and Drug Administration FDA (2021)
European Union	Regulation No. 10/2011 (EU 2011c)	Thapliyal et al. (2024)
European Union	Directive (EU) 2019/904	Thapliyal et al. (2024)

6.2 Gaps and challenges in current regulatory approaches

Despite increasing global efforts to address plastic pollution, notable gaps remain in current regulations. Thus, existing policies often fail to manage the complexity of plastic waste, particularly given the rise of diverse materials and evolving global trade patterns. Furthermore, the lack of enforceable global targets and a coordinated approach has resulted in unorganized and less effective solutions. To address this challenge, it is crucial to explore current policy gaps and the need for better regulatory measures that promote sustainable practices and significantly decrease plastic pollution.

6.2.1 Binding policy instruments

As of 2019, there are no binding global policy instruments with specific and measurable targets for reducing plastic pollution. While recent legally binding amendments to the Basel Convention have made it easier to classify more types of plastic waste and recycle plastic packaging. These amendments do not include measurable targets for reducing plastic pollution, including packaging (Diana et al., 2022). A global program with specific and measurable targets could help unify fragmented national and subnational efforts to combat plastic pollution. This global response would need to be flexible enough to accommodate geographic and cultural differences. Notably, international negotiations led by the UN are currently underway to establish a global plastic treaty by the end of 2024. The ongoing negotiations underscore the recognition of environmental consequences associated with plastic pollution while emphasizing the need to enhance the knowledge base of potential human health risks (Aanesen et al., 2024). This plastic treaty is a legally binding global agreement aiming to address the full lifecycle of plastics, including the design of reusable and recyclable products. The initiative also seeks to enhance international collaboration to facilitate access to technology, capacity building, and scientific and technical cooperation.

In addition, there are many types of plastics and a gap in the plastic life cycle, and many organic pollutants resist degradation, resulting in long-term exposure risks across multiple waterways which involves the development of an approach at multiple levels (international, national) to reduce the plastic pollution of multiple plastic types (Islam et al., 2023). As regulations change, new challenges will arise. For instance, the rise in e-commerce has greatly increased the need for packaging materials, requiring innovative solutions to manage this growth sustainably (Thapliyal et al., 2024). Another growing challenge is the contamination of recycling streams, which can reduce the effectiveness of plastic regulations and recycling programs (Thapliyal et al., 2024).

6.2.2 Recycling regulations and challenges

Concerning plastic recycling regulations, several challenges arise. Firstly, the poor miscibility of polymer blends makes effective sorting of waste crucial for ensuring high-quality products from mechanical recycling. This sorting presents an economic challenge. Moreover, many plastic products are made with additives such as colors, dyes, fillers, UV protectants, fire retardants, reinforcements, and plasticizers (Seay and Ternes, 2022). These additives cause recycled plastics to differ significantly from virgin resins, limiting their suitability for many uses.

Current regulations indicate that only products and materials made from recycled plastic obtained through an authorized recycling procedure may be commercialized. Thus, a suitable quality assurance system must be in place to ensure that the recycled plastic meets the specifications outlined in the relevant regulations (Regulation (EC) No. 2023/2006 Annex) (European Union, 2822008). Therefore, the quality of the plastic input and the recycling process must demonstrate its capability to reduce any contamination of the plastic input to a concentration that does not endanger human health through a challenge test or other appropriate scientific evidence. Hence, the quality of recycled plastic must be assessed and controlled appropriately, ensuring that the finished recycled plastic material complies with established standards.

Finally, over time, plastic becomes unrecyclable and must either be discarded or used for its energy value. This issue is further increased in developing countries, where the infrastructure for collecting and sorting plastic waste is often inadequate or lacking (Seay and Ternes, 2022).

6.3 Effectiveness and enforcement of existing policies

The regulations set by different countries and international organizations play an important role in promoting sustainable practices and protecting the environment from plastic waste. However, the effectiveness of these regulations is not clear and varies between countries. For instance, in Europe, more than EUR 5.5 billion has been designated to enhance waste management capacity, with the goal of recycling an additional 5.8 million tons of plastic waste annually (Nikiema and Asiedu, 2022). An important element of the regulations mentioned above is their effectiveness and implementation. Furthermore, the EU's single-use plastics directive and circular economy action plan have set goals to cut plastic waste. These initiatives have resulted in higher recycling rates, shifting toward eco-friendly materials in the packaging (Directive, 2019). On the other hand, in India, the regulations of plastic bag management seek to reduce waste by promoting the use of compostable and biodegradable materials. These regulations and measures have decreased the demand for plastic bags while there was an increase in the demand for eco-friendly packaging materials (Thapliyal et al., 2024).

The effectiveness of regulations for plastic waste management varies. For example, the ban on plastic waste in many countries aims to enhance efforts to protect the environment and human health. In this context, gradual progress in the developing world is crucial for achieving the sustainability (Islam et al., 2023). To improve waste collection processes, the plastic waste market needs better coordination between demand and supply, along with innovation and investment. Regulations can play a vital role in securing markets for recycled plastics and encouraging producers to create demand (Islam et al., 2023). Additionally, public awareness about MPs can further enhance the effectiveness of these regulations (Nikiema and Asiedu, 2022).

Furthermore, when an economic measure such as a plastic bag tax or fee is introduced, consumers may become accustomed to the higher prices and revert to using more bags, thereby reducing the policy's effectiveness (Diana et al., 2022). The effectiveness of plastic bag policies and the potential demand for paper bags are also often tied to the availability of affordable, reusable alternatives to plastic bags (Diana et al., 2022). Governments around the world offer research grants to support efforts in reducing plastic waste and enforcing regulations. Notable examples include the UK Government's £20 million Plastics Research and Innovation Fund, £61.4 million allocated to the Commonwealth Clean Oceans Alliance, and the EU's Horizon 2020 research and innovation program (Islam et al., 2023). Many countries have developed various technologies to comply with plastic regulations. Among traditional methods, landfilling, and mechanical reprocessing are the most common and easiest to implement on a large scale. Additionally, new technologies are emerging that align with the goals of regulations (Islam et al., 2023).

7 Conclusion

Microplastics have infiltrated various ecosystems and ultimately end up in the ocean, leading to a significant threat for environmental sustainability. The quantification efforts of MPs and their implications for environmental health have been inconsistent with uneven effort across different ecosystems. Marine organisms are impacted by MPs at various structural levels, showing serval harmful effects on essential functions such as the respiratory, reproductive, neurological and immune systems. Future research should be dedicated to modeling MPs transfer across the marine food chain to gain insight into the transfer to higher trophic levels and better understand the impact of this pollution on human life. Overall, the potential loss due to MPs across all marine ecosystem services is estimated to range from 1.22% to 2.1% of global GDP, underscoring the substantial economic burden posed by marine plastic pollution. To better inform policy and management strategies, future research should incorporate comprehensive cost-benefit analyses and advanced economic modeling approaches. Integrating sector-specific losses notably from fisheries, tourism, and ecosystem restoration into these models could provide clearer insights into the long-term economic consequences of MPs pollution and support more effective investment in mitigation measures. The regulatory framework for MPs pollution in the marine environment primarily focuses on restricting intentionally added MPs in products and addressing unintentional releases through standardization and regulatory measures. However, there is currently no regulation specifying threshold levels of MPs in the marine environment and its living resources. Moreover, future regulatory frameworks should prioritize setting quantifiable and enforceable targets for plastic pollution reduction, fostering sustainable practices, and encouraging international collaboration to ensure uniformity in efforts across regions.

Author contributions

MaB: Supervision, Writing – original draft, Investigation, Conceptualization, Writing – review and editing, Resources. AB: Writing – review and editing, Writing – original draft. MA: Writing – original draft, Writing – review and editing. J-CA: Writing – original draft, Writing – review and editing. MN: Writing – review and editing, Writing – original draft. RA: Writing – original draft, Writing – review and editing. YK: Writing – original draft, Writing – review and editing. MoB: Writing – review and editing. AP: Writing – review and editing. LG: Writing – review and editing. WH: Supervision, Funding acquisition, Writing – original draft, Writing – review and editing, Visualization, Validation, Conceptualization.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This manuscript is published as part of the project "Conquering Newstrategiesto Prevent And Reduce Packaging Pollution (MAGNO)" under a Creative Common Public Domain Dedication. MAGNO has been funded by the European Research Executive Agency (REA) under the Horizon Europe programme, grant number 101135258. Funded by the European Union.

Conflict of interest

Author AP was employed by DNV Business Assurance Italy S.r.l.

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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References

Aanesen, M., Ahi, J. C., Abate, T. G., Khan, F. R., De Vries, F. P., Kite-Powell, H., et al. (2024). Insights from international environmental legislation and protocols for the global plastic treaty. *Sci. Rep.* 14, 2750. doi:10.1038/s41598-024-53099-9

Abayomi, O. A., Range, P., Al-Ghouti, M. A., Obbard, J. P., Almeer, S. H., and Ben-Hamadou, R. (2017). Microplastics in coastal environments of the arabian gulf. *Mar. Pollut. Bull.* 124, 181–188. doi:10.1016/j.marpolbul.2017.07.011

Abouda, S., Missawi, O., Cappello, T., Boughattas, I., De Marco, G., Maisano, M., et al. (2022). Toxicological impact of environmental microplastics and benzo[a]pyrene in the seaworm Hediste diversicolor under environmentally relevant exposure conditions. *Environ. Pollut.* 310, 119856. doi:10.1016/j.envpol.2022.119856

Abouda, S., Galati, M., Oliveri Conti, G., Cappello, T., Abelouah, M. R., Romdhani, I., et al. (2024). Metabolomic and biochemical disorders reveal the toxicity of environmental microplastics and benzo[a]pyrene in the marine polychaete Hediste diversicolor. *J. Hazard Mater* 477, 135404. doi:10.1016/j.jhazmat.2024.135404

Adaro, M. E., and Ronda, A. C. (2024). Natural filters of marine microplastic pollution: implications for plants and submerged environments. *Environ. Adv.* 16, 100535. doi:10.1016/j.envadv.2024.100535

Alfonso, M. B., Lindsay, D. J., Arias, A. H., Nakano, H., Jandang, S., and Isobe, A. (2023). Zooplankton as a suitable tool for microplastic research. *Sci. Total Environ.* 905, 167329. doi:10.1016/j.scitotenv.2023.167329

Alimba, C. G., and Faggio, C. (2019). Microplastics in the marine environment: current trends in environmental pollution and mechanisms of toxicological profile. *Environ. Toxicol. Pharmacol.* 68, 61–74. doi:10.1016/j.etap.2019.03.001

Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., et al. (2019). Atmospheric transport and deposition of microplastics in a remote Mountain catchment. *Nat. Geosci.* 12, 339–344. doi:10.1038/s41561-019-0335-5

Amaral-Zettler, L. A., Zettler, E. R., and Mincer, T. J. (2020). Ecology of the plastisphere. *Nat. Rev. Microbiol.* 18, 139–151. doi:10.1038/s41579-019-0308-0

Aminur Rahman, M., Mojumdar, S., Asif, R.Sk, and Marimuthu, K. (2023). Plastic pollution in the ocean: their sources, causes, effects and control measures. *J. Biol. Stud.* 6, 37–52. doi:10.62400/jbs.v6i1.7755

Anderson, D. M., Alpermann, T. J., Cembella, A. D., Collos, Y., Masseret, E., and Montresor, M. (2012). The globally distributed genus alexandrium: multifaceted roles in marine ecosystems and impacts on human health. *Harmful Algae* 14, 10–35. doi:10.1016/j.hal.2011.10.012

Andrady, A. L. (2015). "Persistence of plastic litter in the oceans," in *Mar. Anthropog. Litter*. Editors M. Bergmann, L. Gutow, and M. Klages (Cham: Springer International Publishing), 57–72. doi:10.1007/978-3-319-16510-3_3

Anwaruzzaman, Md, Haque, M. I., Sajol, M. N. I., Habib, M. L., Hasan, M. M., and Kamruzzaman, Md (2022). "Micro and nanoplastic toxicity on aquatic life: fate, effect and remediation strategy,"*Biodegr. Detoxif. Micropollutants Ind. Wastewater*. Elsevier, 145–176. doi:10.1016/B978-0-323-88507-2.00009-9

Arabi, S., and Nahman, A. (2020). Impacts of marine plastic on ecosystem services and economy: state of South African research. *South Afr. J. Sci.* 116. doi:10.17159/sajs.2020/7695

Arlinghaus, R., Abbott, J. K., Fenichel, E. P., Carpenter, S. R., Hunt, L. M., Alós, J., et al. (2019). Governing the recreational dimension of global fisheries. *Proc. Natl. Acad. Sci.* 116, 5209–5213. doi:10.1073/pnas.1902796116

Ashish, J. (2021). *Plastic waste management (amendment) rules government of India*. Ministry of Environment, Forest and Climate Change (MoEFCC.

Atanasova, N., Stoitsova, S., Paunova-Krasteva, T., and Kambourova, M. (2021). Plastic degradation by extremophilic bacteria. *Int. J. Mol. Sci.* 22, 5610. doi:10.3390/ijms22115610

Aung, T., Batish, I., and Ovissipour, R. (2022). Prevalence of microplastics in the eastern oyster *Crassostrea virginica* in the Chesapeake Bay: the impact of different digestion methods on microplastic properties. *Toxics* 10, 29. doi:10.3390/toxics10010029

Auta, H. S., Emenike, C. U., and Fauziah, S. H. (2017). Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. *Environ. Int.* 102, 165–176. doi:10.1016/j.envint.2017.02.013

Ayukai, T. (1987). Discriminate feeding of the calanoid copepod Acartia clausi in mixtures of phytoplankton and inert particles. *Mar. Biol.* 94, 579–587. doi:10.1007/BF00431404

Baak, J. E., Provencher, J. F., and Mallory, M. L. (2020). Plastic ingestion by four seabird species in the Canadian arctic: comparisons across species and time. *Mar. Pollut. Bull.* 158, 111386. doi:10.1016/j.marpolbul.2020.111386

Baechler, B. R., Stienbarger, C. D., Horn, D. A., Joseph, J., Taylor, A. R., Granek, E. F., et al. (2020). Microplastic occurrence and effects in commercially harvested North American finfish and shellfish: current knowledge and future directions. *Limnol. Oceanogr. Lett.* 5, 113–136. doi:10.1002/lol2.10122

Bandh, S. A., Malla, F. A., Qayoom, I., Mohi-Ud-Din, H., Butt, A. K., Altaf, A., et al. (2023). Importance of blue carbon in mitigating climate change and plastic/microplastic pollution and promoting circular economy. *Sustainability* 15, 2682. doi:10.3390/su15032682

Bandini, F., Hchaichi, I., Zitouni, N., Missawi, O., Cocconcelli, P. S., Puglisi, E., et al. (2021). Bacterial community profiling of floating plastics from south mediterranean sites: first evidence of effects on mussels as possible vehicles of transmission. *J. Hazard Mater* 411, 125079. doi:10.1016/j.jhazmat.2021.125079

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* 81, 169–193. doi:10.1890/10-1510.1

Barboza, L. G. A., Dick Vethaak, A., Lavorante, BRBO, Lundebye, A.-K., and Guilhermino, L. (2018). Marine microplastic debris: an emerging issue for food security, food safety and human health. *Mar. Pollut. Bull.* 133, 336–348. doi:10.1016/j.marpolbul.2018.05.047

Battulga, B., Nakayama, M., Matsuoka, S., Kondo, T., Atarashi-Andoh, M., and Koarashi, J. (2024). Dynamics and functions of microbial communities in the plastisphere in temperate coastal environments. *Water Res.* 264, 122207. doi:10.1016/j.watres.2024.122207

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., et al. (2019). Global ecological, social and economic impacts of marine plastic. *Mar. Pollut. Bull.* 142, 189–195. doi:10.1016/j.marpolbul.2019.03.022

Belli, I. M., Cavali, M., Garbossa, L. H. P., Franco, D., Bayard, R., and De Castilhos Junior, A. B. (2024). A review of plastic debris in the south American Atlantic Ocean Coast – distribution, characteristics, policies and legal aspects. *Sci. Total Environ.* 938, 173197. doi:10.1016/j.scitotenv.2024.173197

Ben, I. S., Costa, E., Jaziri, H., Morgana, S., Boukthir, M., Ben Ismail, M. A., et al. (2022). Evolution of the distribution and dynamic of microplastic in water and biota: a study case from the Gulf of Gabes (southern Mediterranean Sea). *Front. Mar. Sci.* 9, 786026. doi:10.3389/fmars.2022.786026

Bergmann, M., and Klages, M. (2012). Increase of litter at the arctic deep-sea observatory HAUSGARTEN. *Mar. Pollut. Bull.* 64, 2734–2741. doi:10.1016/j.marpolbul.2012.09.018

Besseling, E., Wang, B., Lürling, M., and Koelmans, A. A. (2014). Nanoplastic affects growth of *S. obliquus* and reproduction of *D. magna*. *Environ. Sci. Technol.* 48, 12336–12343. doi:10.1021/es503001d

Bhattacharya, P., Lin, S., Turner, J. P., and Ke, P. C. (2010). Physical adsorption of charged plastic nanoparticles affects algal photosynthesis. *J. Phys. Chem. C* 114, 16556–16561. doi:10.1021/jp1054759

Bhuyan, M. S. (2022). Effects of microplastics on fish and in human health. *Front. Environ. Sci.* 10, 827289. doi:10.3389/fenvs.2022.827289

Blettler, M. C. M., Abrial, E., Khan, F. R., Sivri, N., and Espinola, L. A. (2018). Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps. *Water Res.* 143, 416–424. doi:10.1016/j.watres.2018.06.015

Botelho, M. J., Vale, C., Marques, F., Moreirinha, C., Costa, S. T., Guilhermino, L., et al. (2023). One-year variation in quantity and properties of microplastics in mussels (*Mytilus galloprovincialis*) and cockles (*Cerastoderma edule*) from Aveiro lagoon. *Environ. Pollut.* 333, 121949. doi:10.1016/j.envpol.2023.121949

Botterell, Z. L. R., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R. C., and Lindeque, P. K. (2019). Bioavailability and effects of microplastics on marine zooplankton: a review. *Environ. Pollut.* 245, 98–110. doi:10.1016/j.envpol.2018.10.065

Boucher, J., and Friot, D. (2017). *Primary microplastics in the oceans: a global evaluation of sources*. IUCN Gland, Switzerland. doi:10.2305/IUCN.CH.2017.01.en

Boughattas, I., Zitouni, N., Hattab, S., Mkhinini, M., Missawi, O., Helaoui, S., et al. (2022). Interactive effects of environmental microplastics and 2,4-dichlorophenoxyacetic acid (2,4-D) on the earthworm *Eisenia andrei*. *J. Hazard Mater* 424, 127578. doi:10.1016/j.jhazmat.2021.127578

Bowley, J., Baker-Austin, C., Porter, A., Hartnell, R., and Lewis, C. (2021). Oceanic hitchhikers – assessing pathogen risks from marine microplastic. *Trends Microbiol.* 29, 107–116. doi:10.1016/j.tim.2020.06.011

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., and Sukumaran, S. (2020). Plastic rain in protected areas of the United States. *Science* 368, 1257–1260. doi:10.1126/science.aaz5819

Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., et al. (2021). Constraining the atmospheric limb of the plastic cycle. *Proc. Natl. Acad. Sci.* 118, e2020719118. doi:10.1073/pnas.2020719118

Brandts, I., Teles, M., Tvarijonaviciute, A., Pereira, M. L., Martins, M. A., Tort, L., et al. (2018). Effects of polymethylmethacrylate nanoplastics on dicentrarchus labrax. *Genomics* 110, 435–441. doi:10.1016/j.ygeno.2018.10.006

Bråte, I. L. N., Hurley, R., Iversen, K., Beyer, J., Thomas, K. V., Steindal, C. C., et al. (2018). Mytilus spp. as sentinels for monitoring microplastic pollution in Norwegian coastal waters: a qualitative and quantitative study. *Environ. Pollut.* 243, 383–393. doi:10.1016/j.envpol.2018.08.077

Breithaupt, J. L., and Steinmuller, H. E. (2022). Refining the global estimate of mangrove carbon burial rates using sedimentary and geomorphic settings. *Geophys Res. Lett.* 49, e2022GL100177. doi:10.1029/2022GL100177

Bryant, J. A., Clemente, T. M., Viviani, D. A., Fong, A. A., Thomas, K. A., Kemp, P., et al. (2016). Diversity and activity of communities inhabiting plastic debris in the north Pacific gyre. *mSystems* 1, e00024-16–16. doi:10.1128/mSystems.00024-16

Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., et al. (2017). Characteristic of microplastics in the atmospheric fallout from dongguan city, China: preliminary research and first evidence. *Environ. Sci. Pollut. Res.* 24, 24928–24935. doi:10.1007/s11356-017-0116-x

Cai, C., Zhu, L., and Hong, B. (2023). A review of methods for modeling microplastic transport in the marine environments. *Mar. Pollut. Bull.* 193, 115136. doi:10.1016/j.marpolbul.2023.115136

Carlotti, F., Gérigny, O., Bienvenu, D., Ravel, C., Fierro-González, P., Guilloux, L., et al. (2023). Microplastics in the maximum chlorophyll layer along a north-south transect in the Mediterranean Sea in comparison with zooplankton concentrations. *Mar. Pollut. Bull.* 196, 115614. doi:10.1016/j.marpolbul.2023.115614

Carney, A. B., and Eggert, H. (2019). Marine plastic pollution: sources, impacts, and policy issues. *Rev. Environ. Econ. Policy* 13, 317–326. doi:10.1093/reep/rez012

Carson, H. S., Nerheim, M. S., Carroll, K. A., and Eriksen, M. (2013). The plastic-associated microorganisms of the north Pacific gyre. *Mar. Pollut. Bull.* 75, 126–132. doi:10.1016/j.marpolbul.2013.07.054

Chae, Y., and An, Y.-J. (2018). Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. *Environ. Pollut.* 240, 387–395. doi:10.1016/j.envpol.2018.05.008

Chapron, L., Peru, E., Engler, A., Ghiglione, J. F., Meistertzheim, A. L., Pruski, A. M., et al. (2018). Macro- and microplastics affect cold-water corals growth, feeding and behaviour. *Sci. Rep.* 8, 15299. doi:10.1038/s41598-018-33683-6

Charlton-Howard, H. S., Bond, A. L., Rivers-Auty, J., and Lavers, J. L. (2023). Plasticosis': characterising macro- and microplastic-associated fibrosis in seabird tissues. *J. Hazard Mater* 450, 131090. doi:10.1016/j.jhazmat.2023.131090

Chatterjee and Sharma (2019). Microplastics in our oceans and marine health.

Chen, X., Chen, X., Zhao, Y., Zhou, H., Xiong, X., and Wu, C. (2020). Effects of microplastic biofilms on nutrient cycling in simulated freshwater systems. *Sci. Total Environ.* 719, 137276. doi:10.1016/j.scitotenv.2020.137276

Chen, L., Li, J., Tang, Y., Wang, S., Lu, X., Cheng, Z., et al. (2021). Typhoon-induced turbulence redistributed microplastics in coastal areas and reformed plastisphere community. *Water Res.* 204, 117580. doi:10.1016/j.watres.2021.117580

Chen, C.-F., Ju, Y.-R., Lim, Y. C., Wang, M.-H., Chen, C.-W., and Dong, C.-D. (2023). Microplastics in coastal farmed oyster (Crassostrea angulata) shells: Abundance, characteristics, and diversity. *Mar. Pollut. Bull.* 194, 115228. doi:10.1016/j.marpolbul.2023.115228

Cho, Y., Shim, W. J., Jang, M., Han, G. M., and Hong, S. H. (2019). Abundance and characteristics of microplastics in market bivalves from South Korea. *Environ. Pollut.* 245, 1107–1116. doi:10.1016/j.envpol.2018.11.091

Cole, M., and Galloway, T. S. (2015). Ingestion of nanoplastics and microplastics by Pacific oyster larvae. *Environ. Sci. Technol.* 49, 14625–14632. doi:10.1021/acs.est.5b04099

Cole, M., Lindeque, P., Halsband, C., and Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: a review. *Mar. Pollut. Bull.* 62, 2588–2597. doi:10.1016/j.marpolbul.2011.09.025

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., et al. (2013). Microplastic ingestion by zooplankton. *Environ. Sci. Technol.* 47, 6646–6655. doi:10.1021/es400663f

Cole, M., Lindeque, P., Fileman, E., Halsband, C., and Galloway, T. S. (2015). The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. *Environ. Sci. Technol.* 49, 1130–1137. doi:10.1021/es504525u

Collignon, A., Hecq, J.-H., Galgani, F., Collard, F., and Goffart, A. (2014). Annual variation in neustonic micro- and meso-plastic particles and zooplankton in the Bay of calvi (Mediterranean–Corsica). *Mar. Pollut. Bull.* 79, 293–298. doi:10.1016/j.marpolbul.2013.11.023

Conke, L. S., and Nascimento, E. P. D. (2018). A coleta seletiva nas pesquisas brasileiras: uma avaliação metodológica. *Urbe Rev. Bras. Gest. Urbana* 10, 199–212. doi:10.1590/2175-3369.010.001.ao14

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi:10.1038/387253a0

Courtene-Jones, W., Van Gennip, S., Penicaud, J., Penn, E., and Thompson, R. C. (2022). Synthetic microplastic abundance and composition along a longitudinal gradient traversing the subtropical gyre in the north Atlantic Ocean. *Mar. Pollut. Bull.* 185, 114371. doi:10.1016/j.marpolbul.2022.114371

Cowger, W., Booth, A. M., Hamilton, B. M., Thaysen, C., Primpke, S., Munno, K., et al. (2020). Reporting guidelines to increase the reproducibility and comparability of research on microplastics. *Appl. Spectrosc.* 74, 1066–1077. doi:10.1177/0003702820930292

Cózar, A., Echevarría, F., González-Gordillo, J. I., Irigoien, X., Úbeda, B., Hernández-León, S., et al. (2014). Plastic debris in the open ocean. *Proc. Natl. Acad. Sci.* 111, 10239–10244. doi:10.1073/pnas.1314705111

Da Costa, J. P., and Duarte, A. C. (2020). "Introduction to the analytical methodologies for the analysis of microplastics," in *Handb. Microplastics environ.* Editors T. Rocha-Santos, M. Costa, and C. Mouneyrac (Cham: Springer International Publishing), 1–31. doi:10.1007/978-3-030-10618-8_1-1

Davidov, K., Marsay, K. S., Itzahri, S., Rubin-Blum, M., Sobral, P., Kranzler, C. F., et al. (2024). Community composition and seasonal dynamics of microplastic biota in the eastern Mediterranean Sea. *Sci. Rep.* 14, 26131. doi:10.1038/s41598-024-73281-3

De Sá, L. C., Luís, L. G., and Guilhermino, L. (2015). Effects of microplastics on juveniles of the common goby (pomatoschistus microps): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. *Environ. Pollut.* 196, 359–362. doi:10.1016/j.envpol.2014.10.026

Desforges, J.-P. W., Galbraith, M., Dangerfield, N., and Ross, P. S. (2014). Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. *Mar. Pollut. Bull.* 79, 94–99. doi:10.1016/j.marpolbul.2013.12.035

Desforges, J.-P. W., Galbraith, M., and Ross, P. S. (2015). Ingestion of microplastics by zooplankton in the northeast Pacific Ocean. *Arch. Environ. Contam. Toxicol.* 69, 320–330. doi:10.1007/s00244-015-0172-5

Dey, S., Rout, A. K., Behera, B. K., and Ghosh, K. (2022). Plastisphere community assemblage of aquatic environment: plastic-microbe interaction, role in degradation and characterization technologies. *Environ. Microbiome* 17, 32. doi:10.1186/s40793-022-00430-4

Diana, Z., Vegh, T., Karasik, R., Bering, J., D. Llano Caldas, J., Pickle, A., et al. (2022). The evolving global plastics policy landscape: an inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi:10.1016/j.envsci.2022.03.028

Ding, J., Li, J., Sun, C., Jiang, F., He, C., Zhang, M., et al. (2020). An examination of the occurrence and potential risks of microplastics across various shellfish. *Sci. Total Environ.* 739, 139887. doi:10.1016/j.scitotenv.2020.139887

Ding, J., Sun, C., Li, J., Shi, H., Xu, X., Ju, P., et al. (2022). Microplastics in global bivalve mollusks: a call for protocol standardization. *J. Hazard Mater* 438, 129490. doi:10.1016/j.jhazmat.2022.129490

Directive, E. U. (2019). Directive (EU) 2019/904 of the European parliament and of the council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.

Di Renzo, L., Mascilongo, G., Berti, M., Bogdanović, T., Listeš, E., Brkljača, M., et al. (2021). Potential impact of microplastics and additives on the health status of loggerhead turtles (caretta caretta) stranded along the central adriatic Coast. *Water Air Soil Pollut.* 232, 98. doi:10.1007/s11270-021-04994-8

Djekoun, M., Gaaied, S., Romdhani, I., Mohamed Rida, A., Missaoui, Y., Boubekeur, M. S., et al. (2024). Abundance and distribution of environmental microplastic in edible fish and mussels from the south mediterranean coasts. *Mar. Pollut. Bull.* 206, 116705. doi:10.1016/j.marpolbul.2024.116705

Dris, R., Gasperi, J., Saad, M., Mirande, C., and Tassin, B. (2016). Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? *Mar. Pollut. Bull.* 104, 290–293. doi:10.1016/j.marpolbul.2016.01.006

Dris, R., Gasperi, J., and Tassin, B. (2018). "Sources and fate of microplastics in urban areas: a focus on paris megacity,". *Freshw. Microplastics*. Editors M. Wagner, and S. Lambert (Cham: Springer International Publishing), 58, 69–83. doi:10.1007/978-3-319-61615-5_4

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., and Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* 3, 961–968. doi:10.1038/nclimate1970

Dube, E., and Okuthe, G. E. (2023). Plastics and Micro/nano-plastics (MNPs) in the environment: occurrence, impact, and toxicity. *Int. J. Environ. Res. Public Health* 20, 6667. doi:10.3390/ijerph20176667

Dussud, C., Hudec, C., George, M., Fabre, P., Higgs, P., Bruzaud, S., et al. (2018). Colonization of non-biodegradable and biodegradable plastics by marine microorganisms. *Front. Microbiol.* 9, 1571. doi:10.3389/fmicb.2018.01571

Eerkes-Medrano, D., Thompson, R. C., and Aldridge, D. C. (2015). Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Res.* 75, 63–82. doi:10.1016/j.watres.2015.02.012

Eich, A., Mildenberger, T., Laforsch, C., and Weber, M. (2015). Biofilm and diatom succession on polyethylene (PE) and biodegradable plastic bags in two marine habitats: early signs of degradation in the pelagic and benthic zone? *PLOS ONE* 10, e0137201. doi:10.1371/journal.pone.0137201

Engler, R. E. (2012). The complex interaction between marine debris and toxic chemicals in the ocean. *Environ. Sci. Technol.* 46, 12302–12315. doi:10.1021/es3027105

Eurofins. Ensuring Food Contact Safety: Key Requirements and Documentation (2022). *Eurofins Sci. Irel.*

European Union (2022). *Commission regulation (EC) no 282/2008 of march 27, 2008, on recycled plastic materials and articles intended to come into contact with foods and amending regulation (EC).* EU.

European Union Recycled plastic materials and articles intended to come into contact with foods and amending regulation (EC) no 2023/2006. *Official J. Eur. Union, L* 86, 9–18. (Comm Regul EC No 2822008 27 March 20082008).

Evangeliou, N., Tichý, O., Eckhardt, S., Zwaaftink, C. G., and Brahney, J. (2022). Sources and fate of atmospheric microplastics revealed from inverse and dispersion modelling: from global emissions to deposition. *J. Hazard Mater* 432, 128585. doi:10.1016/j.jhazmat.2022.128585

Fackelmann, G., Pham, C. K., Rodríguez, Y., Mallory, M. L., Provencher, J. F., Baak, J. E., et al. (2023). Current levels of microplastic pollution impact wild seabird gut microbiomes. *Nat. Ecol. Evol.* 7, 698–706. doi:10.1038/s41559-023-02013-z

Fagiano, V., Alomar, C., Compa, M., Soto-Navarro, J., Jordá, G., and Deudero, S. (2022). Neustonic microplastics and zooplankton in coastal waters of cabrera marine protected area (western Mediterranean Sea). *Sci. Total Environ.* 804, 150120. doi:10.1016/j.scitotenv.2021.150120

FAO (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. Available online at: https://doi.org/10.4060/ca9229en.

FAO (2024). The State of World Fisheries and Aquaculture 2024 - Blue Transformation in action. Rome. Available online at: https://doi.org/10.4060/cd0683en.

Farrell, P., and Nelson, K. (2013). Trophic level transfer of microplastic: mytilus edulis (L.) to carcinus maenas (L.). *Environ. Pollut.* 177, 1–3. doi:10.1016/j.envpol.2013.01.046

FDA (2020). Recycled plastics in food packaging. *Food Contact Subst. FCS.*

Fernández, F. (1979). Particle selection in the nauplius of *Calanus pacificus*. *J. Plankton Res.* 1, 313–328. doi:10.1093/plankt/1.4.313

Fernández Severini, M. D., Villagran, D. M., Buzzi, N. S., and Sartor, G. C. (2019). Microplastics in oysters (*Crassostrea gigas*) and water at the Bahía blanca Estuary (southwestern Atlantic): an emerging issue of global concern. *Reg. Stud. Mar. Sci.* 32, 100829. doi:10.1016/j.rsma.2019.100829

Ferreira, G. V. B., Barletta, M., Lima, A. R. A., Morley, S. A., Justino, A. K. S., and Costa, M. F. (2018). High intake rates of microplastics in a Western Atlantic predatory fish, and insights of a direct fishery effect. *Environ. Pollut.* 236, 706–717. doi:10.1016/j.envpol.2018.01.095

Fishfarming Expert (2025). A could on the horizon.

Food and Agriculture Organization of the United Nations (2024). *State of world fisheries and Aquaculture-blue transformation in action. s.l.* FOOD and AGRICULTURE ORG.

Food and Drug Administration (FDA) (2021). Guidance for industry: use of recycled plastics in food packaging: chemistry considerations.

Fossi, M. C., Pedà, C., Compa, M., Tsangaris, C., Alomar, C., Claro, F., et al. (2018). Bioindicators for monitoring marine litter ingestion and its impacts on mediterranean biodiversity. *Environ. Pollut.* 237, 1023–1040. doi:10.1016/j.envpol.2017.11.019

Frère, L., Maignien, L., Chalopin, M., Huvet, A., Rinnert, E., Morrison, H., et al. (2018). Microplastic bacterial communities in the Bay of brest: influence of polymer type and size. *Environ. Pollut.* 242, 614–625. doi:10.1016/j.envpol.2018.07.023

Gajšt, T., Bizjak, T., Palatinus, A., Liubartseva, S., and Kržan, A. (2016). Sea surface microplastics in Slovenian part of the northern adriatic. *Mar. Pollut. Bull.* 113, 392–399. doi:10.1016/j.marpolbul.2016.10.031

Galgani, F., Hanke, G., and Maes, T. (2015). in *Global distribution, composition and abundance of marine litter* Editors M. Bergmann, L. Gutow, M. Klages, and M. A. Litter Cham: Springer International Publishing, 29–56. doi:10.1007/978-3-319-16510-3_2

Galgani, L., Tzempelikou, E., Kalantzi, I., Tsiola, A., Tsapakis, M., Pitta, P., et al. (2023). Marine plastics alter the organic matter composition of the air-sea boundary layer, with influences on CO2 exchange: a large-scale analysis method to explore future ocean scenarios. *Sci. Total Environ.* 857, 159624. doi:10.1016/j.scitotenv.2022.159624

Galgani, F., Lusher, A. L., Strand, J., Haarr, M. L., Vinci, M., Molina Jack, E., et al. (2024). Revisiting the strategy for marine litter monitoring within the european marine strategy framework directive (MSFD). *Ocean. Coast Manag.* 255, 107254. doi:10.1016/j.ocecoaman.2024.107254

Galloway, T. S. (2015). "Micro- and nano-plastics and human health," in *Mar. Anthropog. Litter* Editors M. Bergmann, L. Gutow, and M. Klages (Cham: Springer International Publishing), 343–366. doi:10.1007/978-3-319-16510-3_13

Galloway, T. S., Cole, M., and Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. *Nat. Ecol. Evol.* 1, 0116. doi:10.1038/s41559-017-0116

Gao, S., Orlowski, N., Bopf, F. K., and Breuer, L. (2024). A review on microplastics in major european Rivers. *WIREs Water* 11, e1713. doi:10.1002/wat2.1713

Garcés-Ordóñez, O., Castillo-Olaya, V. A., Granados-Briceño, A. F., Blandón García, L. M., and Espinosa Díaz, L. F. (2019). Marine litter and microplastic pollution on mangrove soils of the Ciénaga Grande de Santa Marta, Colombian Caribbean. *Mar. Pollut. Bull.* 145, 455–462. doi:10.1016/j.marpolbul.2019.06.058

Gewert, B., Plassmann, M. M., and MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. *Environ. Sci. Process Impacts* 17, 1513–1521. doi:10.1039/C5EM00207A

Gigault, J., El Hadri, H., Nguyen, B., Grassl, B., Rowenczyk, L., Tufenkji, N., et al. (2021). Nanoplastics are neither microplastics nor engineered nanoparticles. *Nat. Nanotechnol.* 16, 501–507. doi:10.1038/s41565-021-00886-4

Goldstein, M. C., and Goodwin, D. S. (2013). Gooseneck barnacles (*lepas* spp.) ingest microplastic debris in the north Pacific subtropical gyre. *PeerJ* 1, e184. doi:10.7717/peerj.184

González-Soto, N., Hatfield, J., Katsumiti, A., Duroudier, N., Lacave, J. M., Bilbao, E., et al. (2019). Impacts of dietary exposure to different sized polystyrene microplastics alone and with sorbed benzo[a]pyrene on biomarkers and whole organism responses in mussels *Mytilus galloprovincialis*. *Sci. Total Environ.* 684, 548–566. doi:10.1016/j.scitotenv.2019.05.161

Goss, H., Jaskiel, J., and Rotjan, R. (2018). Thalassia testudinum as a potential vector for incorporating microplastics into benthic marine food webs. *Mar. Pollut. Bull.* 135, 1085–1089. doi:10.1016/j.marpolbul.2018.08.024

GOV. UK (2022). The plastic packaging tax (general) regulations.

Green, D. S., Boots, B., Sigwart, J., Jiang, S., and Rocha, C. (2016). Effects of conventional and biodegradable microplastics on a marine ecosystem engineer (arenicola marina) and sediment nutrient cycling. *Environ. Pollut.* 208, 426–434. doi:10.1016/j.envpol.2015.10.010

Gu, W., Liu, S., Chen, L., Liu, Y., Gu, C., Ren, H., et al. (2020). Single-cell RNA sequencing reveals size-dependent effects of polystyrene microplastics on immune and secretory cell populations from zebrafish intestines. *Environ. Sci. Technol.* 54, 3417–3427. doi:10.1021/acs.est.9b06386

Gündoğdu, S., Çevik, C., Ayat, B., Aydoğan, B., and Karaca, S. (2018). How microplastics quantities increase with flood events? An example from Mersin Bay NE levantine Coast of Turkey. *Environ. Pollut.* 239, 342–350. doi:10.1016/j.envpol.2018.04.042

Guo, X., Chen, Y.-R., Sun, X., Li, C., Hou, L., Liu, M., et al. (2022). Plastic properties affect the composition of prokaryotic and eukaryotic communities and further regulate the ARGs in their surface biofilms. *Sci. Total Environ.* 839, 156362. doi:10.1016/j.scitotenv.2022.156362

Habib, D., Locke, D. C., and Cannone, L. J. (1998). Synthetic fibers as indicators of municipal sewage sludge, sludge products, and sewage treatment plant effluents. *Water Air Soil Pollut.* 103, 1–8. doi:10.1023/A:1004908110793

Habumugisha, T., Zhang, Z., Uwizewe, C., Yan, C., Ndayishimiye, J. C., Rehman, A., et al. (2024). Toxicological review of micro- and nano-plastics in aquatic environments: risks to ecosystems, food web dynamics and human health. *Ecotoxicol. Environ. Saf.* 278, 116426. doi:10.1016/j.ecoenv.2024.116426

Hadiyanto, H., Khoironi, A., Dianratri, I., Suherman, S., Muhammad, F., and Vaidyanathan, S. (2021). Interactions between polyethylene and polypropylene microplastics and spirulina sp. microalgae in aquatic systems. *Heliyon* 7, e07676. doi:10.1016/j.heliyon.2021.e07676

Hale, R. C., Seeley, M. E., La Guardia, M. J., Mai, L., and Zeng, E. Y. (2020). A global perspective on microplastics. *J. Geophys Res. Oceans* 125, e2018JC014719. doi:10.1029/2018JC014719

Hamd, W., Daher, E. A., Tofa, T. S., and Dutta, J. (2022). Recent advances in photocatalytic removal of microplastics: mechanisms, kinetic degradation, and reactor design. *Front. Mar. Sci.* 9, 885614. doi:10.3389/fmars.2022.885614

Hankins, C., Moso, E., and Lasseigne, D. (2021). Microplastics impair growth in two Atlantic scleractinian coral species, Pseudodiploria clivosa and Acropora cervicornis. *Environ. Pollut.* 275, 116649. doi:10.1016/j.envpol.2021.116649

Harrison, J. P., Schratzberger, M., Sapp, M., and Osborn, A. M. (2014). Rapid bacterial colonization of low-density polyethylene microplastics in coastal sediment microcosms. *BMC Microbiol.* 14, 232. doi:10.1186/s12866-014-0232-4

Harvey, B. P., Kerfahi, D., Jung, Y., Shin, J.-H., Adams, J. M., and Hall-Spencer, J. M. (2020). Ocean acidification alters bacterial communities on marine plastic debris. *Mar. Pollut. Bull.* 161, 111749. doi:10.1016/j.marpolbul.2020.111749

Hattab, S., Boughattas, I., Alaya, C., Gaaied, S., Romdhani, I., El Gaied, F., et al. (2024a). Assessing the presence of microplastic in agriculture soils irrigated with treated waste waters using lumbricus sp.: ecotoxicological effects. *Sci. Total Environ.* 950, 175096. doi:10.1016/j.scitotenv.2024.175096

Hattab, S., Cappello, T., Boughattas, I., Sassi, K., Mkhinini, M., Zitouni, N., et al. (2024b). Toxicity assessment of animal manure composts containing environmental microplastics by using earthworms *Eisenia andrei*. *Sci. Total Environ.* 931, 172975. doi:10.1016/j.scitotenv.2024.172975

Hermabessiere, L., Paul-Pont, I., Cassone, A.-L., Himber, C., Receveur, J., Jezequel, R., et al. (2019). Microplastic contamination and pollutant levels in mussels and cockles collected along the channel coasts. *Environ. Pollut.* 250, 807–819. doi:10.1016/j.envpol.2019.04.051

Hildebrandt, L., El Gareb, F., Zimmermann, T., Klein, O., Kerstan, A., Emeis, K.-C., et al. (2022). Spatial distribution of microplastics in the tropical Indian Ocean based on laser direct infrared imaging and microwave-assisted matrix digestion. *Environ. Pollut.* 307, 119547. doi:10.1016/j.envpol.2022.119547

Historic day in the campaign to beat plastic pollution: nations commit to develop a legally binding agreement n.d.

Hitchcock, J. N. (2022). Microplastics can alter phytoplankton community composition. *Sci. Total Environ.* 819, 153074. doi:10.1016/j.scitotenv.2022.153074

Hossain, S., Shukri, Z. N. A., Iber, B. T., Yatim, N. I., Manan, H., Rahman, T., et al. (2024). Microplastic pollution in shellfish aquaculture: occurrence, impact, and possible remedies. *Water Air Soil Pollut.* 235, 240. doi:10.1007/s11270-024-07033-4

Huang, Y., Xiao, X., Xu, C., Perianen, Y. D., Hu, J., and Holmer, M. (2020). Seagrass beds acting as a trap of microplastics - emerging hotspot in the coastal region? *Environ. Pollut.* 257, 113450. doi:10.1016/j.envpol.2019.113450

Huang, W., Song, B., Liang, J., Niu, Q., Zeng, G., Shen, M., et al. (2021). Microplastics and associated contaminants in the aquatic environment: a review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. *J. Hazard Mater* 405, 124187. doi:10.1016/j.jhazmat.2020.124187

Islam, M. S., Lee, Z., Shaleh, A., and Soo, H. S. (2023). The united nations environment assembly resolution to end plastic pollution: challenges to effective policy interventions. *Environ. Dev. Sustain* 26, 10927–10944. doi:10.1007/s10668-023-03639-6

Isobe, A., and Iwasaki, S. (2022). The fate of missing ocean plastics: are they just a marine environmental problem? *Sci. Total Environ.* 825, 153935. doi:10.1016/j.scitotenv.2022.153935

Jacob, H., Besson, M., Swarzenski, P. W., Lecchini, D., and Metian, M. (2020). Effects of virgin Micro- and nanoplastics on fish: trends, meta-analysis, and perspectives. *Environ. Sci. Technol.* 54, 4733–4745. doi:10.1021/acs.est.9b05995

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi:10.1126/science.1260352

Janakiram, R., Keerthivasan, R., Janani, R., Ramasundaram, S., Martin, M. V., Venkatesan, R., et al. (2023). Seasonal distribution of microplastics in surface waters of the northern Indian Ocean. *Mar. Pollut. Bull.* 190, 114838. doi:10.1016/j.marpolbul.2023.114838

Jandang, S., Alfonso, M. B., Nakano, H., Phinchan, N., Darumas, U., Viyakarn, V., et al. (2024). Possible sink of missing ocean plastic: accumulation patterns in reef-building corals in the gulf of Thailand. *Sci. Total Environ.* 954, 176210. doi:10.1016/j.scitotenv.2024.176210

Jang, Y. C., Hong, S., Lee, J., Lee, M. J., and Shim, W. J. (2014). Estimation of lost tourism revenue in geoje island from the 2011 marine debris pollution event in South Korea. *Mar. Pollut. Bull.* 81, 49–54. doi:10.1016/j.marpolbul.2014.02.021

Jani, P. U., McCarthy, D. E., and Florence, A. T. (1992). Nanosphere and microsphere uptake *via* Peyer's patches: observation of the rate of uptake in the rat after a single oral dose. *Int. J. Pharm.* 86, 239–246. doi:10.1016/0378-5173(92)90202-d

Jin, C., Luo, T., Zhu, Z., Pan, Z., Yang, J., Wang, W., et al. (2017). Imazalil exposure induces gut microbiota dysbiosis and hepatic metabolism disorder in zebrafish. *Comp. Biochem. Physiol. Part C Toxicol. Pharmacol.* 202, 85–93. doi:10.1016/j.cbpc.2017.08.007

Jolaosho, T. L., Rasaq, M. F., Omotoye, E. V., Araomo, O. V., Adekoya, O. S., Abolaji, O. Y., et al. (2025). Microplastics in freshwater and marine ecosystems: occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions. *Ecotoxicol. Environ. Saf.* 294, 118036. doi:10.1016/j.ecoenv.2025.118036

Kane, I. A., Clare, M. A., Miramontes, E., Wogelius, R., Rothwell, J. J., Garreau, P., et al. (2020). Seafloor microplastic hotspots controlled by deep-sea circulation. *Science* 368, 1140–1145. doi:10.1126/science.aba5899

Kazour, M., Jemaa, S., Issa, C., Khalaf, G., and Amara, R. (2019). Microplastics pollution along the Lebanese Coast (eastern Mediterranean Basin): occurrence in surface water, sediments and biota samples. *Sci. Total Environ.* 696, 133933. doi:10.1016/j.scitotenv.2019.133933

Khalid, N., Aqeel, M., Noman, A., Hashem, M., Mostafa, Y. S., Alhaithloul, H. A. S., et al. (2021). Linking effects of microplastics to ecological impacts in marine environments. *Chemosphere* 264, 128541. doi:10.1016/j.chemosphere.2020.128541

Khan, S. A. (2020). Clearly hazardous, obscurely regulated: lessons from the basel convention on waste trade, 114, 200, 205. doi:10.1017/aju.2020.38

Kida, M., Ziembowicz, S., and Koszelnik, P. (2023). Decomposition of microplastics: emission of harmful substances and greenhouse gases in the environment. *J. Environ. Chem. Eng.* 11, 109047. doi:10.1016/j.jece.2022.109047

Kiki, C., Adéoyé, A. B. E., Li, X., Yan, X., Feng, J., Yu, C.-P., et al. (2023). Contrasting effects of phytoplankton aging on microplastic antibiotic adsorption depending on species tolerance, and biofouling level. *Water Res.* 237, 119992. doi:10.1016/j.watres.2023.119992

Kiørboe, T. (2001). Formation and fate of marine snow: small-scale processes with large-scale implications. *Sci* 65, 57–71. doi:10.3989/scimar.2001.65s257

Kirstein, I. V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., et al. (2016). Dangerous hitchhikers? Evidence for potentially pathogenic vibrio spp. on microplastic particles. *Mar. Environ. Res.* 120, 1–8. doi:10.1016/j.marenvres.2016.07.004

Koelmans, A. A., Bakir, A., Burton, G. A., and Janssen, C. R. (2016). Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. *Environ. Sci. Technol.* 50, 3315–3326. doi:10.1021/acs.est.5b06069

Koh, J., Bairoliya, S., Salta, M., Cho, Z. T., Fong, J., Neo, M. L., et al. (2023). Sediment-driven plastisphere community assembly on plastic debris in tropical coastal and marine environments. *Environ. Int.* 179, 108153. doi:10.1016/j.envint.2023.108153

Kole, P. J., Löhr, A. J., Van Belleghem, F., and Ragas, A. (2017). Wear and tear of tyres: a stealthy source of microplastics in the environment. *Int. J. Environ. Res. Public Health* 14, 1265. doi:10.3390/ijerph14101265

Kühn, S., Bravo Rebolledo, E. L., and Van Franeker, J. A. (2015). "Deleterious effects of litter on marine life," in *Mar. Anthropog. Litter* Editors M. Bergmann, L. Gutow, and M. Klages (Cham: Springer International Publishing), 75–116. doi:10.1007/978-3-319-16510-3_4

Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D. W., and Law, K. L. (2012). The effect of wind mixing on the vertical distribution of buoyant plastic debris. *Geophys Res. Lett.* 39, 2012GL051116. doi:10.1029/2012GL051116

Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P. K., et al. (2021). Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* 13, 9963. doi:10.3390/su13179963

Lacerda, A. L. d. F., Taylor, J. D., Rodrigues, L. d.S., Kessler, F., Secchi, E., and Proietti, M. C. (2022). Floating plastics and their associated biota in the Western south Atlantic. *Sci. Total Environ.* 805, 150186. doi:10.1016/j.scitotenv.2021.150186

Lacerda, A. L., Frias, J., and Pedrotti, M. L. (2024). Tardigrades in the marine plastisphere: new hitchhikers surfing plastics. *Mar. Pollut. Bull.* 200, 116071. doi:10.1016/j.marpolbul.2024.116071

Lamichhane, G., Acharya, A., Marahatha, R., Modi, B., Paudel, R., Adhikari, A., et al. (2023). Microplastics in environment: global concern, challenges, and controlling measures. *Int. J. Environ. Sci. Technol.* 20, 4673–4694. doi:10.1007/s13762-022-04261-1

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science* 369, 1455–1461. doi:10.1126/science.aba9475

Law, K. L., and Thompson, R. C. (2014). Microplastics in the seas. *Science* 345, 144–145. doi:10.1126/science.1254065

Lear, G., Kingsbury, J. M., Franchini, S., Gambarini, V., Maday, S. D. M., Wallbank, J. A., et al. (2021). Plastics and the microbiome: impacts and solutions. *Environ. Microbiome* 16, 2. doi:10.1186/s40793-020-00371-w

Lear, G., Maday, S. D. M., Gambarini, V., Northcott, G., Abbel, R., Kingsbury, J. M., et al. (2022). Microbial abilities to degrade global environmental plastic polymer waste are overstated. *Environ. Res. Lett.* 17, 043002. doi:10.1088/1748-9326/ac59a7

Lebreton, L. (2022). The status and fate of Oceanic garbage patches. *Nat. Rev. Earth Environ.* 3, 730–732. doi:10.1038/s43017-022-00363-z

Lebreton, L., and Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Commun.* 5, 6. doi:10.1057/s41599-018-0212-7

Lebreton, L. C.-M., and Borrero, J. C. (2013). Modeling the transport and accumulation floating debris generated by the 11 march 2011 tohoku tsunami. *Mar. Pollut. Bull.* 66, 53–58. doi:10.1016/j.marpolbul.2012.11.013

Lebreton, L. C.-M., Greer, S. D., and Borrero, J. C. (2012). Numerical modelling of floating debris in the world's oceans. *Mar. Pollut. Bull.* 64, 653–661. doi:10.1016/j.marpolbul.2011.10.027

Lebreton, L. C. M., Van Der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nat. Commun.* 8, 15611. doi:10.1038/ncomms15611

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., et al. (2018). Evidence that the great Pacific garbage patch is rapidly accumulating plastic. *Sci. Rep.* 8, 4666. doi:10.1038/s41598-018-22939-w

Lebreton, L., Royer, S.-J., Peytavin, A., Strietman, W. J., Smeding-Zuurendonk, I., and Egger, M. (2022). Industrialised fishing nations largely contribute to floating plastic pollution in the north Pacific subtropical gyre. *Sci. Rep.* 12, 12666. doi:10.1038/s41598-022-16529-0

Li, Y. (2022). Legislation and policy on pollution prevention and the control of marine microplastics. *Water* 14, 2790. doi:10.3390/w14182790

Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., et al. (2016). Microplastics in mussels along the coastal waters of China. *Environ. Pollut.* 214, 177–184. doi:10.1016/j.envpol.2016.04.012

Li, C., Busquets, R., and Campos, L. C. (2020a). Assessment of microplastics in freshwater systems: a review. *Sci. Total Environ.* 707, 135578. doi:10.1016/j.scitotenv.2019.135578

Li, L.-L., Amara, R., Souissi, S., Dehaut, A., Duflos, G., and Monchy, S. (2020b). Impacts of microplastics exposure on mussel (*Mytilus edulis*) gut microbiota. *Sci. Total Environ.* 745, 141018. doi:10.1016/j.scitotenv.2020.141018

Li, R., Yu, L., Chai, M., Wu, H., and Zhu, X. (2020c). The distribution, characteristics and ecological risks of microplastics in the mangroves of southern China. *Sci. Total Environ.* 708, 135025. doi:10.1016/j.scitotenv.2019.135025

Li, J., Wang, Z., Rotchell, J. M., Shen, X., Li, Q., and Zhu, J. (2021a). Where are we? Towards an understanding of the selective accumulation of microplastics in mussels. *Environ. Pollut.* 286, 117543. doi:10.1016/j.envpol.2021.117543

Li, Q., Ma, C., Zhang, Q., and Shi, H. (2021b). Microplastics in shellfish and implications for food safety. *Curr. Opin. Food Sci.* 40, 192–197. doi:10.1016/j.cofs.2021.04.017

Li, H., Chen, H., Wang, J., Li, J., Liu, S., Tu, J., et al. (2021c). Influence of microplastics on the growth and the intestinal microbiota composition of brine shrimp. *Front. Microbiol.* 12, 717272. doi:10.3389/fmicb.2021.717272

Li, W., Zu, B., Hu, L., Lan, L., Zhang, Y., and Li, J. (2022a). Migration behaviors of microplastics in sediment-bearing turbulence: aggregation, settlement, and resuspension. *Mar. Pollut. Bull.* 180, 113775. doi:10.1016/j.marpolbul.2022.113775

Li, R., Zhu, L., Cui, L., and Zhu, Y.-G. (2022b). Viral diversity and potential environmental risk in microplastic at watershed scale: evidence from metagenomic analysis of plastisphere. *Environ. Int.* 161, 107146. doi:10.1016/j.envint.2022.107146

Li, R., Nie, J., Qiu, D., Li, S., Sun, Y., and Wang, C. (2023a). Toxic effect of chronic exposure to polyethylene nano/microplastics on oxidative stress, neurotoxicity and gut microbiota of adult zebrafish (*Danio rerio*). *Chemosphere* 339, 139774. doi:10.1016/j.chemosphere.2023.139774

Li, C., Zhu, L., Li, W.-T., and Li, D. (2023b). Microplastics in the seagrass ecosystems: a critical review. *Sci. Total Environ.* 902, 166152. doi:10.1016/j.scitotenv.2023.166152

Li, Y., Zhu, Y., Huang, J., Ho, Y.-W., Fang, J. K.-H., and Lam, E. Y. (2024a). High-throughput microplastic assessment using polarization holographic imaging. *Sci. Rep.* 14, 2355. doi:10.1038/s41598-024-52762-5

Li, K., Du, L., Qin, C., Bolan, N., Wang, H., and Wang, H. (2024b). Microplastic pollution as an environmental risk exacerbating the greenhouse effect and climate change: a review. *Carbon Res.* 3, 9. doi:10.1007/s44246-023-00097-7

Liang, W., Li, B., Jong, M.-C., Ma, C., Zuo, C., Chen, Q., et al. (2023). Process-oriented impacts of microplastic fibers on behavior and histology of fish. *J. Hazard Mater* 448, 130856. doi:10.1016/j.jhazmat.2023.130856

Lin, H.-T., Schneider, F., Aziz, M. A., Wong, K. Y., Arunachalam, K. D., Praveena, S. M., et al. (2024). Microplastics in Asian Rivers: geographical distribution, Most detected types, and inconsistency in methodologies. *Environ. Pollut.* 349, 123985. doi:10.1016/j.envpol.2024.123985

Liss, P. S. (2020). Microplastics: all up in the air? *Mar. Pollut. Bull.* 153, 110952. doi:10.1016/j.marpolbul.2020.110952

Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., and Li, D. (2019a). Source and potential risk assessment of suspended atmospheric microplastics in shanghai. *Sci. Total Environ.* 675, 462–471. doi:10.1016/j.scitotenv.2019.04.110

Liu, K., Wu, T., Wang, X., Song, Z., Zong, C., Wei, N., et al. (2019b). Consistent transport of terrestrial microplastics to the ocean through atmosphere. *Environ. Sci. Technol.* 53, 10612–10619. doi:10.1021/acs.est.9b03427

Liu, G., Jiang, R., You, J., Muir, D. C. G., and Zeng, E. Y. (2020). Microplastic impacts on microalgae growth: effects of size and humic acid. *Environ. Sci. Technol.* 54, 1782–1789. doi:10.1021/acs.est.9b06187

Liubartseva, S., Coppini, G., Lecci, R., and Clementi, E. (2018). Tracking plastics in the mediterranean: 2D Lagrangian model. *Mar. Pollut. Bull.* 129, 151–162. doi:10.1016/j.marpolbul.2018.02.019

Lobelle, D., and Cunliffe, M. (2011). Early microbial biofilm formation on marine plastic debris. *Mar. Pollut. Bull.* 62, 197–200. doi:10.1016/j.marpolbul.2010.10.013

Lu, J., Zhang, Y., Wu, J., and Luo, Y. (2019). Effects of microplastics on distribution of antibiotic resistance genes in recirculating aquaculture system. *Ecotoxicol. Environ. Saf.* 184, 109631. doi:10.1016/j.ecoenv.2019.109631

Lu, H.-C., Ziajahromi, S., Neale, P. A., and Leusch, F. D. L. (2021). A systematic review of freshwater microplastics in water and sediments: recommendations for harmonisation to enhance future study comparisons. *Sci. Total Environ.* 781, 146693. doi:10.1016/j.scitotenv.2021.146693

Luís, L. G., Ferreira, P., Fonte, E., Oliveira, M., and Guilhermino, L. (2015). Does the presence of microplastics influence the acute toxicity of chromium(VI) to early juveniles of the common goby (pomatoschistus microps)? A study with juveniles from two wild estuarine populations. *Aquat. Toxicol.* 164, 163–174. doi:10.1016/j.aquatox.2015.04.018

Lusher, A. L., McHugh, M., and Thompson, R. C. (2013). Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Mar. Pollut. Bull.* 67, 94–99. doi:10.1016/j.marpolbul.2012.11.028

Lusher, A. L., Tirelli, V., O'Connor, I., and Officer, R. (2015a). Microplastics in arctic polar waters: the first reported values of particles in surface and sub-surface samples. *Sci. Rep.* 5, 14947. doi:10.1038/srep14947

Lusher, A. L., Hernandez-Milian, G., O'Brien, J., Berrow, S., O'Connor, I., and Officer, R. (2015b). Microplastic and macroplastic ingestion by a deep diving, Oceanic cetacean: the True's beaked whale Mesoplodon mirus. *Environ. Pollut.* 199, 185–191. doi:10.1016/j.envpol.2015.01.023

Lusher, A., Hollman, P. C. H., and Mendoza-Hill, J. (2017). Microplastics in fisheries and aquaculture: status of knowledge on their occurrence and implications for aquatic organisms and food safety.

MacCready, P., and Geyer, W. R. (2010). Advances in estuarine physics. *Annu. Rev. Mar. Sci.* 2, 35–58. doi:10.1146/annurev-marine-120308-081015

Macfadyen, G., Huntington, T., and Cappell, R. (2009). *Abandoned, lost or otherwise discarded fishing gear*. United Nations Environment Programme: Food and Agriculture Organization of the United Nations.

Macreadie, P. I., Nielsen, D. A., Kelleway, J. J., Atwood, T. B., Seymour, J. R., Petrou, K., et al. (2017). Can we manage coastal ecosystems to sequester more blue carbon? *Front. Ecol. Environ.* 15, 206–213. doi:10.1002/fee.1484

Malinowski, C. R., Searle, C. L., Schaber, J., and Höök, T. O. (2023). Microplastics impact simple aquatic food web dynamics through reduced zooplankton feeding and potentially releasing algae from consumer control. *Sci. Total Environ.* 904, 166691. doi:10.1016/j.scitotenv.2023.166691

Manríquez-Guzmán, D. L., Chaparro-Herrera, D. J., and Ramírez-García, P. (2023). Microplastics are transferred in a trophic web between zooplankton and the amphibian axolotl (ambystoma mexicanum): effects on their feeding behavior. *Food Webs* 37, e00316. doi:10.1016/j.fooweb.2023.e00316

Marana, M. H., Poulsen, R., Thormar, E. A., Clausen, C. G., Thit, A., Mathiessen, H., et al. (2022). Plastic nanoparticles cause mild inflammation, disrupt metabolic pathways, change the gut microbiota and affect reproduction in zebrafish: a full generation multi-omics study. *J. Hazard Mater* 424, 127705. doi:10.1016/j.jhazmat.2021.127705

MARPOL (1973). International convention for the prevention of pollution from ships (MARPOL).

Masó, M., Garcés, E., Pagès, F., and Camp, J. (2003). Drifting plastic debris as a potential vector for dispersing harmful algal bloom (HAB) species. *Sci* 67, 107–111. doi:10.3989/scimar.2003.67n1107

Masó, M., Fortuño, J. M., De Juan, S., and Demestre, M. (2016). Microfouling communities from pelagic and benthic marine plastic debris sampled across mediterranean coastal waters. *Sci* 80, 117–127. doi:10.3989/scimar.04281.10A

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., et al. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Front. Ecol. Environ.* 9, 552–560. doi:10.1890/110004

Meijer, L. J. J., Van Emmerik, T., Van Der Ent, R., Schmidt, C., and Lebreton, L. (2021). More than 1000 Rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.* 7, eaaz5803. doi:10.1126/sciadv.aaz5803

Merrill, G. B., Hermabessiere, L., Rochman, C. M., and Nowacek, D. P. (2023). Microplastics in marine mammal blubber, melon, and other tissues: evidence of translocation. *Environ. Pollut.* 335, 122252. doi:10.1016/j.envpol.2023.122252

Microplastic pollution in marine environment (2021). occurrence, fate, and effects (with a specific focus on biogeochemical carbon and nitrogen cycles). *Sustain. Text. Prod. Process. Manuf. Chem.*, Singapore: Springer Singapore, p. 105–126. doi:10.1007/978-981-16-0297-9_4

Miguel, I., Santos, A., Venâncio, C., and Oliveira, M. (2024). Knowledge, concerns and attitudes towards plastic pollution: an empirical study of public perceptions in Portugal. *Sci. Total Environ.* 906, 167784. doi:10.1016/j.scitotenv.2023.167784

Ministry of the Environment, Japan. (2021). The plastic resource circulation act.

Missawi, O., Bousserrhine, N., Belbekhouche, S., Zitouni, N., Alphonse, V., Boughattas, I., et al. (2020). Abundance and distribution of small microplastics (≤3 µm) in sediments and seaworms from the southern mediterranean coasts and characterisation of their potential harmful effects. *Environ. Pollut.* 263, 114634. doi:10.1016/j.envpol.2020.114634

Missawi, O., Bousserrhine, N., Zitouni, N., Maisano, M., Boughattas, I., De Marco, G., et al. (2021). Uptake, accumulation and associated cellular alterations of environmental samples of microplastics in the seaworm Hediste diversicolor. *J. Hazard Mater* 406, 124287. doi:10.1016/j.jhazmat.2020.124287

Missawi, O., Venditti, M., Cappello, T., Zitouni, N., Marco, G.De, Boughattas, I., et al. (2022). Autophagic event and metabolomic disorders unveil cellular toxicity of environmental microplastics on marine polychaete Hediste diversicolor. *Environ. Pollut.* 302, 119106. doi:10.1016/j.envpol.2022.119106

Morgana, S., Ghigliotti, L., Estévez-Calvar, N., Stifanese, R., Wieckzorek, A., Doyle, T., et al. (2018). Microplastics in the arctic: a case study with sub-surface water and fish samples off northeast Greenland. *Environ. Pollut.* 242, 1078–1086. doi:10.1016/j.envpol.2018.08.001

Mouat, J., Lopez Lozano, R., and Bateson, H. (2010). Economic impacts of marine litter.

Mouchi, V., Chapron, L., Peru, E., Pruski, A. M., Meistertzheim, A.-L., Vétion, G., et al. (2019). Long-term aquaria study suggests species-specific responses of two cold-water corals to macro-and microplastics exposure. *Environ. Pollut.* 253, 322–329. doi:10.1016/j.envpol.2019.07.024

Murano, C., Nonnis, S., Scalvini, F. G., Maffioli, E., Corsi, I., Tedeschi, G., et al. (2023). Response to microplastic exposure: an exploration into the sea urchin immune cell proteome. *Environ. Pollut.* 320, 121062. doi:10.1016/j.envpol.2023.121062

Muriel-Millán, L. F., Millán-López, S., and Pardo-López, L. (2021). Biotechnological applications of marine bacteria in bioremediation of environments polluted with hydrocarbons and plastics. *Appl. Microbiol. Biotechnol.* 105, 7171–7185. doi:10.1007/s00253-021-11569-4

Murphy, F., Ewins, C., Carbonnier, F., and Quinn, B. (2016). Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. *Environ. Sci. Technol.* 50, 5800–5808. doi:10.1021/acs.est.5b05416

Murray, C. C., Maximenko, N., and Lippiatt, S. (2018). The influx of marine debris from the great Japan tsunami of 2011 to North American shorelines. *Mar. Pollut. Bull.* 132, 26–32. doi:10.1016/j.marpolbul.2018.01.004

Mutuku, J., Yanotti, M., Tocock, M., and Hatton MacDonald, D. (2024). The abundance of microplastics in the world's oceans: a systematic review. *Oceans* 5, 398–428. doi:10.3390/oceans5030024

Naidoo, T., Rajkaran, A., and Sershen, (2020). Impacts of plastic debris on biota and implications for human health: a South African perspective. *South Afr. J. Sci.* 116. doi:10.17159/sajs.2020/7693

Naidu, S. A., Mawii, L., Ranga Rao, V., Anitha, G., Mishra, P., Narayanaswamy, B. E., et al. (2021). Characterization of plastic debris from surface waters of the eastern arabian sea–indian ocean. *Mar. Pollut. Bull.* 169, 112468. doi:10.1016/j.marpolbul.2021.112468

Nakad, M., Gardelle, L., and Abboud, R. J. (2024). A systematic review of the different methods assessing sustainability integration in engineering curricula. *Sustainability* 16, 4549. doi:10.3390/su16114549

Nakad, M., Gardelle, L., and Abboud, R. J. (2025a). Stimulating engineering students' potential for sustainable development. *Sustainability* 17, 1073. doi:10.3390/su17031073

Nakad, M., Charif, H., Gardelle, L., and Abboud, R. J. (2025b). Empowering sustainability: can women engineers play a key role in achieving a sustainable future? *Sustain Futur* 10, 100977. doi:10.1016/j.sftr.2025.100977

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., and Beas, I. N. (2021). An overview of plastic waste generation and management in food packaging industries. *Recycling* 6, 12. doi:10.3390/recycling6010012

Nelms, S. E., Duncan, E. M., Broderick, A. C., Galloway, T. S., Godfrey, M. H., Hamann, M., et al. (2016). Plastic and marine turtles: a review and call for research. *ICES J. Mar. Sci. J. Cons.* 73, 165–181. doi:10.1093/icesjms/fsv165

Nelms, S. E., Galloway, T. S., Godley, B. J., Jarvis, D. S., and Lindeque, P. K. (2018). Investigating microplastic trophic transfer in marine top predators. *Environ. Pollut.* 238, 999–1007. doi:10.1016/j.envpol.2018.02.016

Nikiema, J., and Asiedu, Z. (2022). A review of the cost and effectiveness of solutions to address plastic pollution. *Environ. Sci. Pollut. Res.* 29, 24547–24573. doi:10.1007/s11356-021-18038-5

Nizzetto, L., Futter, M., and Langaas, S. (2016). Are agricultural soils dumps for microplastics of urban origin? *Environ. Sci. Technol.* 50, 10777–10779. doi:10.1021/acs.est.6b04140

Noman, M. A., Adyel, T. M., Macreadie, P. I., and Trevathan-Tackett, S. M. (2024). Prioritising plastic pollution research in blue carbon ecosystems: a scientometric overview. *Sci. Total Environ.* 914, 169868. doi:10.1016/j.scitotenv.2024.169868

Ogbuagu, C. C., Kassem, H., Udiba, U. U., Stead, J. L., and Cundy, A. B. (2022). Role of saltmarsh systems in estuarine trapping of microplastics. *Sci. Rep.* 12, 15546. doi:10.1038/s41598-022-18881-7

Oliveira, A. R., Sardinha-Silva, A., Andrews, P. L. R., Green, D., Cooke, G. M., Hall, S., et al. (2020). Microplastics presence in cultured and wild-caught cuttlefish, Sepia officinalis. *Mar. Pollut. Bull.* 160, 111553. doi:10.1016/j.marpolbul.2020.111553

Pamanji, R., Kumareshan, T. N., Priya, S. L., Sivan, G., and Selvin, J. (2024). Exploring the impact of antibiotics, microplastics, nanoparticles, and pesticides on zebrafish gut microbiomes: insights into composition, interactions, and health implications. *Chemosphere* 349, 140867. doi:10.1016/j.chemosphere.2023.140867

Pan, Z., Liu, Q., Sun, Y., Sun, X., and Lin, H. (2019). Environmental implications of microplastic pollution in the northwestern Pacific Ocean. *Mar. Pollut. Bull.* 146, 215–224. doi:10.1016/j.marpolbul.2019.06.031

Panti, C., Baini, M., Lusher, A., Hernandez-Milan, G., Bravo Rebolledo, E. L., Unger, B., et al. (2019). Marine litter: one of the major threats for marine mammals. Outcomes from the european cetacean society workshop. *Environ. Pollut.* 247, 72–79. doi:10.1016/j.envpol.2019.01.029

Pappoe, C., Palm, L. M. N.-D., Denutsui, D., Boateng, C. M., Danso-Abbeam, H., and Serfor-Armah, Y. (2022). Occurrence of microplastics in gastrointestinal tract of fish from the Gulf of Guinea, Ghana. *Mar. Pollut. Bull.* 182, 113955. doi:10.1016/j.marpolbul.2022.113955

Parsons, M. L., Aligizaki, K., Bottein, M.-Y. D., Fraga, S., Morton, S. L., Penna, A., et al. (2012). Gambierdiscus and ostreopsis: reassessment of the state of knowledge of their taxonomy, geography, ecophysiology, and toxicology. *Harmful Algae* 14, 107–129. doi:10.1016/j.hal.2011.10.017

Pedà, C., Caccamo, L., Fossi, M. C., Gai, F., Andaloro, F., Genovese, L., et al. (2016). Intestinal alterations in European sea bass dicentrarchus Labrax (linnaeus, 1758) exposed to microplastics: preliminary results. *Environ. Pollut.* 212, 251–256. doi:10.1016/j.envpol.2016.01.083

Pegado, TDSES, Schmid, K., Winemiller, K. O., Chelazzi, D., Cincinelli, A., Dei, L., et al. (2018). First evidence of microplastic ingestion by fishes from the amazon river Estuary. *Mar. Pollut. Bull.* 133, 814–821. doi:10.1016/j.marpolbul.2018.06.035

Pencik, O., Molnarova, K., Durdakova, M., Kolackova, M., Klofac, D., Kucsera, A., et al. (2023). Not so dangerous? PET microplastics toxicity on freshwater microalgae and Cyanobacteria. *Environ. Pollut.* 329, 121628. doi:10.1016/j.envpol.2023.121628

Pendleton, L. H., Thébaud, O., Mongruel, R. C., and Levrel, H. (2016). Has the value of global marine and coastal ecosystem services changed? *Mar. Policy* 64, 156–158. doi:10.1016/j.marpol.2015.11.018

Pereira, L. G., Ferreira, G. V. B., Justino, A. K. S., De Oliveira, K. M. T., De Queiroz, M. T., Schmidt, N., et al. (2023). Exploring microplastic contamination in guiana dolphins (sotalia guianensis): insights into plastic pollution in the Southwestern tropical Atlantic. *Mar. Pollut. Bull.* 194, 115407. doi:10.1016/j.marpolbul.2023.115407

Petersen, F., and Hubbart, J. A. (2021). The occurrence and transport of microplastics: the state of the science. *Sci. Total Environ.* 758, 143936. doi:10.1016/j.scitotenv.2020.143936

Phelan, A., Meissner, K., Humphrey, J., and Ross, H. (2022). Plastic pollution and packaging: corporate commitments and actions from the food and beverage sector. *J. Clean. Prod.* 331, 129827. doi:10.1016/j.jclepro.2021.129827

Pimentel, D., Zuniga, R., and Morrison, D. (2005). Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecol. Econ.* 52, 273–288. doi:10.1016/j.ecolecon.2004.10.002

Pinheiro, L. M., Britz, L. M. K., Agostini, V. O., Pérez-Parada, A., García-Rodríguez, F., Galloway, T. S., et al. (2022). Salt marshes as the final watershed fate for meso- and microplastic contamination: a case study from southern Brazil. *Sci. Total Environ.* 838, 156077. doi:10.1016/j.scitotenv.2022.156077

Pirotta, E., Thomas, L., Costa, D. P., Hall, A. J., Harris, C. M., Harwood, J., et al. (2022). Understanding the combined effects of multiple stressors: a new perspective on a longstanding challenge. *Sci. Total Environ.* 821, 153322. doi:10.1016/j.scitotenv.2022.153322

Pivokonský, M., Pivokonská, L., Novotná, K., Čermáková, L., and Klimtová, M. (2020). Occurrence and fate of microplastics at two different drinking water treatment plants within a river catchment. *Sci. Total Environ.* 741, 140236. doi:10.1016/j.scitotenv.2020.140236

Plastics Europe (2020). Plastics Europe.

Plastics Europe (2021). Plastics Europe.

Prata, J. C., Da Costa, J. P., Lopes, I., Duarte, A. C., and Rocha-Santos, T. (2019). Effects of microplastics on microalgae populations: a critical review. *Sci. Total Environ.* 665, 400–405. doi:10.1016/j.scitotenv.2019.02.132

Priyadharshini, S., Jeyavani, J., Al-Ghanim, K. A., Govindarajan, M., Karthikeyan, S., and Vaseeharan, B. (2024). Eco-toxicity assessment of polypropylene microplastics in juvenile zebrafish (*Danio rerio*). *J. Contam. Hydrol.* 266, 104415. doi:10.1016/j.jconhyd.2024.104415

Qian, J., Tang, S., Wang, P., Lu, B., Li, K., Jin, W., et al. (2021). From source to sink: review and prospects of microplastics in wetland ecosystems. *Sci. Total Environ.* 758, 143633. doi:10.1016/j.scitotenv.2020.143633

Qiao, R., Deng, Y., Zhang, S., Wolosker, M. B., Zhu, Q., Ren, H., et al. (2019a). Accumulation of different shapes of microplastics initiates intestinal injury and gut microbiota dysbiosis in the gut of zebrafish. *Chemosphere* 236, 124334. doi:10.1016/j.chemosphere.2019.07.065

Qiao, R., Sheng, C., Lu, Y., Zhang, Y., Ren, H., and Lemos, B. (2019b). Microplastics induce intestinal inflammation, oxidative stress, and disorders of metabolome and microbiome in zebrafish. *Sci. Total Environ.* 662, 246–253. doi:10.1016/j.scitotenv.2019.01.245

Queiroz, AFDS, Da Conceição, A. S., Chelazzi, D., Rollnic, M., Cincinelli, A., Giarrizzo, T., et al. (2022). First assessment of microplastic and artificial microfiber contamination in surface waters of the amazon Continental shelf. *Sci. Total Environ.* 839, 156259. doi:10.1016/j.scitotenv.2022.156259

Radisic, V., Nimje, P. S., Bienfait, A. M., and Marathe, N. P. (2020). Marine plastics from Norwegian West Coast carry potentially virulent fish pathogens and opportunistic human pathogens harboring new variants of antibiotic resistance genes. *Microorganisms* 8, 1200. doi:10.3390/microorganisms8081200

Raes, L., Mittempergher, D., and Jain, A. (2023). *The economic impact of plastic pollution, and the benefits of reducing mismanaged waste*. Gland, Switzerland: IUCN.

Rafa, N., Ahmed, B., Zohora, F., Bakya, J., Ahmed, S., Ahmed, S. F., et al. (2024). Microplastics as carriers of toxic pollutants: source, transport, and toxicological effects. *Environ. Pollut.* 343, 123190. doi:10.1016/j.envpol.2023.123190

Raghul, S. S., Bhat, S. G., Chandrasekaran, M., Francis, V., and Thachil, E. T. (2014). Biodegradation of polyvinyl alcohol-low linear density polyethylene-blended plastic film by consortium of marine benthic vibrios. *Int. J. Environ. Sci. Technol.* 11, 1827–1834. doi:10.1007/s13762-013-0335-8

Rahman, M. N., Shozib, S. H., MstY, A., Islam, A. R. M. T., Islam, M. S., Sohel, M. S., et al. (2023). Microplastic as an invisible threat to the coral reefs: sources, toxicity mechanisms, policy intervention, and the way forward. *J. Hazard Mater* 454, 131522. doi:10.1016/j.jhazmat.2023.131522

Rasool, F. N., Saavedra, M. A., Pamba, S., Perold, V., Mmochi, A. J., Maalim, M., et al. (2021). Isolation and characterization of human pathogenic multidrug resistant bacteria associated with plastic litter collected in zanzibar. *J. Hazard Mater* 405, 124591. doi:10.1016/j.jhazmat.2020.124591

Reid, W. V., Mooney, H. A., Cropper, Capistrano, A.D., Carpenter, S.R., and Chopra, K. *Ecosystems and human well-being: synthesis; a report of the millennium ecosystem assessment*. Washington, DC: Island Press.

Reisser, J., Shaw, J., Hallegraeff, G., Proietti, M., Barnes, D. K. A., Thums, M., et al. (2014). Millimeter-sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. *PLoS ONE* 9, e100289. doi:10.1371/journal.pone.0100289

Rhein, S., and Schmid, M. (2020). Consumers' awareness of plastic packaging: more than just environmental concerns. *Resour. Conserv. Recycl* 162, 105063. doi:10.1016/j.resconrec.2020.105063

Rochman, C. M., Tahir, A., Williams, S. L., Baxa, D. V., Lam, R., Miller, J. T., et al. (2015). Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Sci. Rep.* 5, 14340. doi:10.1038/srep14340

Rodrigues, A., Oliver, D. M., McCarron, A., and Quilliam, R. S. (2019). Colonisation of plastic pellets (nurdles) by *E. coli* at public bathing beaches. *Mar. Pollut. Bull.* 139, 376–380. doi:10.1016/j.marpolbul.2019.01.011

Romdhani, I., De Marco, G., Cappello, T., Ibala, S., Zitouni, N., Boughattas, I., et al. (2022). Impact of environmental microplastics alone and mixed with benzo[a]pyrene on cellular and molecular responses of *Mytilus galloprovincialis*. *J. Hazard Mater* 435, 128952. doi:10.1016/j.jhazmat.2022.128952

Romdhani, I., Gallo, A., Venditti, M., Abelouah, M. R., Varchetta, R., Najahi, H., et al. (2024). Unveiling the impact of environmental microplastics on mussel spermatozoa: first evidence of prothymosin-α detection in invertebrate's Male gametes. *J. Hazard Mater* 461, 132521. doi:10.1016/j.jhazmat.2023.132521

Ronda, A. C., Arias, A. H., Oliva, A. L., and Marcovecchio, J. E. (2019). Synthetic microfibers in marine sediments and surface seawater from the argentinean Continental shelf and a marine protected area. *Mar. Pollut. Bull.* 149, 110618. doi:10.1016/j.marpolbul.2019.110618

Rummel, C. D., Jahnke, A., Gorokhova, E., Kühnel, D., and Schmitt-Jansen, M. (2017). Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environ. Sci. Technol. Lett.* 4, 258–267. doi:10.1021/acs.estlett.7b00164

Rummel-Bulska, I. (2007). The basel convention and its implementation. *Waste Manag. Ser.*, vol. 4, 133–169. doi:10.1016/S0713-2743(04)80009-6

Sababadichetty, L., Miltgen, G., Vincent, B., Guilhaumon, F., Lenoble, V., Thibault, M., et al. (2024). Microplastics in the Insular marine environment of the southwest Indian Ocean carry a microbiome including antimicrobial resistant (AMR) bacteria: a case study from Reunion island. *Mar. Pollut. Bull.* 198, 115911. doi:10.1016/j.marpolbul.2023.115911

Şahin, B., Belivermiş, M., Demiralp, S., Sezer, N., Bektaş, S., Kaptan, E., et al. (2024). The multistressor effect of pH reduction, microplastic and lanthanum on sea urchin Arbacia lixula. *Mar. Pollut. Bull.* 205, 116638. doi:10.1016/j.marpolbul.2024.116638

Saikumar, S., Mani, R., Ganesan, S., and Ganesan, M. (2024). Evaluating the impact of the combined acute toxicity of iron (fe) and microplastics on namalycastis jaya. *Aquat. Toxicol.* 277, 107141. doi:10.1016/j.aquatox.2024.107141

Santos, R. G., Machovsky-Capuska, G. E., and Andrades, R. (2021). Plastic ingestion as an evolutionary trap: toward a holistic understanding. *Science* 373, 56–60. doi:10.1126/science.abh0945

Savoca, M. S., McInturf, A. G., and Hazen, E. L. (2021). Plastic ingestion by marine fish is widespread and increasing. *Glob. Change Biol.* 27, 2188–2199. doi:10.1111/gcb.15533

Schmidt, C., Krauth, T., and Wagner, S. (2017). Export of plastic debris by Rivers into the sea. *Environ. Sci. Technol.* 51, 12246–12253. doi:10.1021/acs.est.7b02368

Schmidt, N., Thibault, D., Galgani, F., Paluselli, A., and Sempéré, R. (2018). Occurrence of microplastics in surface waters of the Gulf of Lion (NW Mediterranean Sea). *Prog. Oceanogr.* 163, 214–220. doi:10.1016/j.pocean.2017.11.010

Schymanski, D., Goldbeck, C., Humpf, H.-U., and Fürst, P. (2018). Analysis of microplastics in water by micro-raman spectroscopy: release of plastic particles from different packaging into mineral water. *Water Res.* 129, 154–162. doi:10.1016/j.watres.2017.11.011

Seay, J., and Ternes, M. E. (2022). A review of current challenges and legal advances in the global management of plastic waste. *Clean. Technol. Environ. Policy* 24, 731–738. doi:10.1007/s10098-022-02289-y

Seeley, M. E., Song, B., Passie, R., and Hale, R. C. (2020). Microplastics affect sedimentary microbial communities and nitrogen cycling. *Nat. Commun.* 11, 2372. doi:10.1038/s41467-020-16235-3

Senate Bill, C. (2022). Plastic pollution prevention and packaging producer responsibility act, 54.

Shen, M., Ye, S., Zeng, G., Zhang, Y., Xing, L., Tang, W., et al. (2020). Can microplastics pose a threat to ocean carbon sequestration? *Mar. Pollut. Bull.* 150, 110712. doi:10.1016/j.marpolbul.2019.110712

Sherrington, C. (2016). Plastics in the marine environment.

Shiu, R.-F., Vazquez, C. I., Chiang, C.-Y., Chiu, M.-H., Chen, C.-S., Ni, C.-W., et al. (2020). Nano- and microplastics trigger secretion of protein-rich extracellular polymeric substances from phytoplankton. *Sci. Total Environ.* 748, 141469. doi:10.1016/j.scitotenv.2020.141469

Siddiqui, S. A., Profeta, A., Decker, T., Smetana, S., and Menrad, K. (2023). Influencing factors for consumers' intention to reduce plastic packaging in different groups of fast-moving consumer goods in Germany. *Sustainability* 15, 7625. doi:10.3390/su15097625

Silva, M. M., Maldonado, G. C., Castro, R. O., De Sá Felizardo, J., Cardoso, R. P., Anjos, R. M. D., et al. (2019). Dispersal of potentially pathogenic bacteria by plastic debris in Guanabara Bay, RJ, Brazil. *Mar. Pollut. Bull.* 141, 561–568. doi:10.1016/j.marpolbul.2019.02.064

Simon-Sánchez, L., Grelaud, M., Franci, M., and Ziveri, P. (2022). Are research methods shaping our understanding of microplastic pollution? A literature review on the seawater and sediment bodies of the Mediterranean Sea. *Environ. Pollut.* 292, 118275. doi:10.1016/j.envpol.2021.118275

Sjollema, S. B., Redondo-Hasselerharm, P., Leslie, H. A., Kraak, M. H. S., and Vethaak, A. D. (2016). Do plastic particles affect microalgal photosynthesis and growth? *Aquat. Toxicol.* 170, 259–261. doi:10.1016/j.aquatox.2015.12.002

Smith, M., Love, D. C., Rochman, C. M., and Neff, R. A. (2018). Microplastics in seafood and the implications for human health. *Curr. Environ. Health Rep.* 5, 375–386. doi:10.1007/s40572-018-0206-z

Spalding, M., Burke, L., Wood, S. A., Ashpole, J., Hutchison, J., and Zu Ermgassen, P. (2017). Mapping the global value and distribution of coral reef tourism. *Mar. Policy* 82, 104–113. doi:10.1016/j.marpol.2017.05.014

Squadrone, S., Biancani, B., Da Rugna, C., Favaro, L., Pederiva, S., and Abete, M. C. (2022). Trace and rare Earth element bioaccumulation in the spotted dogfish (*Scyliorhinus stellaris*). *Environ. Sci. Pollut. Res.* 29, 70262–70268. doi:10.1007/s11356-022-20886-8

Sridharan, S., Kumar, M., Bolan, N. S., Singh, L., Kumar, S., Kumar, R., et al. (2021). Are microplastics destabilizing the global network of terrestrial and aquatic ecosystem services? *Environ. Res.* 198, 111243. doi:10.1016/j.envres.2021.111243

Steensgaard, I. M., Syberg, K., Rist, S., Hartmann, N. B., Boldrin, A., and Hansen, S. F. (2017). From macro-to microplastics - analysis of EU regulation along the life cycle of plastic bags. *Environ. Pollut.* 224, 289–299. doi:10.1016/j.envpol.2017.02.007

Strafella, P., López Correa, M., Pyko, I., Teichert, S., and Gomiero, A. (2022). "Distribution of microplastics in the marine environment," in *Handb. Microplastics environ.* Editors T. Rocha-Santos, M. F. Costa, and C. Mouneyrac (Cham: Springer International Publishing), 813–847. doi:10.1007/978-3-030-39041-9_43

Su, X., Yang, L., Yang, K., Tang, Y., Wen, T., Wang, Y., et al. (2022). Estuarine plastisphere as an overlooked source of N2O production. *Nat. Commun.* 13, 3884. doi:10.1038/s41467-022-31584-x

Suaria, G., and Aliani, S. (2014). Floating debris in the Mediterranean Sea. *Mar. Pollut. Bull.* 86, 494–504. doi:10.1016/j.marpolbul.2014.06.025

Suaria, G., Avio, C. G., Mineo, A., Lattin, G. L., Magaldi, M. G., Belmonte, G., et al. (2016). The mediterranean plastic soup: synthetic polymers in mediterranean surface waters. *Sci. Rep.* 6, 37551. doi:10.1038/srep37551

Sun, Y., Li, H., Zhang, J., Wang, H., Cui, X., Gao, X., et al. (2024). Assembly mechanisms of microbial communities in plastisphere related to species taxonomic types and habitat niches. *Mar. Pollut. Bull.* 198, 115894. doi:10.1016/j.marpolbul.2023.115894

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M. E. J., et al. (2016). Oyster reproduction is affected by exposure to polystyrene microplastics. *Proc. Natl. Acad. Sci.* 113, 2430–2435. doi:10.1073/pnas.1519019113

Tamura, Y., Takai, Y., Miyamoto, H., SeokHyun, L., Liu, Y., Qiu, X., et al. (2024). Alteration of shoaling behavior and dysbiosis in the gut of medaka (*Oryzias latipes*) exposed to 2-μm polystyrene microplastics. *Chemosphere* 353, 141643. doi:10.1016/j.chemosphere.2024.141643

Tekman, M. B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., et al. (2020). Tying up loose ends of microplastic pollution in the arctic: distribution from the sea surface through the water column to deep-sea sediments at the HAUSGARTEN observatory. *Environ. Sci. Technol.* 54, 4079–4090. doi:10.1021/acs.est.9b06981

Ten Brink, P., Schweitzer, J., Watkins, E., and Howe, H. (2016). *Marine litter: socio-Economic study*. Inst Eur Environ Policy IEEP.

Thapliyal, D., Karale, M., Diwan, V., Kumra, S., Arya, R. K., and Verros, G. D. (2024). Current status of sustainable food packaging regulations: global perspective. *Sustainability* 16, 5554. doi:10.3390/su16135554

Thery, J., Li, L.-L., Das, S., Dufour, D., Benali, S., Raquez, J.-M., et al. (2023). Multigenerational exposure of microplastics on the microbiota of *E. affinis* (copepod): a comparative study between biodegradable and nonbiodegradable microplastics. *Front. Ecol. Evol.* 11, 1231346. doi:10.3389/fevo.2023.1231346

Thibault, M., Hoarau, L., Lebreton, L., Le Corre, M., Barret, M., Cordier, E., et al. (2023). Do loggerhead sea turtle (caretta caretta) gut contents reflect the types, colors and sources of plastic pollution in the southwest Indian Ocean? *Mar. Pollut. Bull.* 194, 115343. doi:10.1016/j.marpolbul.2023.115343

Thompson, R. C. (2015). "Microplastics in the marine environment: sources, consequences and solutions," in *Mar. Anthropog. Litter* Editors M. Bergmann, L. Gutow, and M. Klages (Cham: Springer International Publishing), 185–200. doi:10.1007/978-3-319-16510-3_7

Tian, R., Guan, M., Chen, L., Wan, Y., He, L., Zhao, Z., et al. (2024). Mechanism insights into the histopathological changes of polypropylene microplastics induced gut and liver in zebrafish. *Ecotoxicol. Environ. Saf.* 280, 116537. doi:10.1016/j.ecoenv.2024.116537

Tourinho, P. S., Kočí, V., Loureiro, S., and Van Gestel, C. A. M. (2019). Partitioning of chemical contaminants to microplastics: sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation. *Environ. Pollut.* 252, 1246–1256. doi:10.1016/j.envpol.2019.06.030

Trainer, V. L., Bates, S. S., Lundholm, N., Thessen, A. E., Cochlan, W. P., Adams, N. G., et al. (2012). Pseudo-nitzschia physiological ecology, phylogeny, toxicity, monitoring and impacts on ecosystem health. *Harmful Algae* 14, 271–300. doi:10.1016/j.hal.2011.10.025

Trowbridge, J. H., and Lentz, S. J. (2018). The bottom boundary layer. *Annu. Rev. Mar. Sci.* 10, 397–420. doi:10.1146/annurev-marine-121916-063351

Tunali, M., Uzoefuna, E. N., Tunali, M. M., and Yenigun, O. (2020). Effect of microplastics and microplastic-metal combinations on growth and chlorophyll a concentration of Chlorella vulgaris. *Sci. Total Environ.* 743, 140479. doi:10.1016/j.scitotenv.2020.140479

Tuuri, E. M., and Leterme, S. C. (2023). How plastic debris and associated chemicals impact the marine food web: a review. *Environ. Pollut.* 321, 121156. doi:10.1016/j.envpol.2023.121156

Uheida, A., Mejía, H. G., Abdel-Rehim, M., Hamd, W., and Dutta, J. (2021). Visible light photocatalytic degradation of polypropylene microplastics in a continuous water flow system. *J. Hazard Mater* 406, 124299. doi:10.1016/j.jhazmat.2020.124299

UNEP (2014). Valuing plastic: the business case for measuring, managing and disclosing plastic use in the consumer goods industry.

UNEP (2016). Marine plastic debris and microplastics: global lessons and research to inspire action and guide policy change.

UNEP (2022). *Historic day in the campaign to beat plastic pollution: nations commit to develop a legally binding agreement*. Nairobi, Kenya: UNEP.

Urban-Malinga, B., Jakubowska, M., and Białowąs, M. (2021). Response of sediment-dwelling bivalves to microplastics and its potential implications for benthic processes. *Sci. Total Environ.* 769, 144302. doi:10.1016/j.scitotenv.2020.144302

Usman, S., Razis, A. F. A., Shaari, K., Azmai, M. N. A., Saad, M. Z., Isa, N. M., et al. (2022). Polystyrene microplastics induce gut microbiome and metabolome changes in Javanese medaka fish (*Oryzias javanicus* bleeker, 1854). *Toxicol. Rep.* 9, 1369–1379. doi:10.1016/j.toxrep.2022.05.001

Vaksmaa, A., Hernando-Morales, V., Zeghal, E., and Niemann, H. (2021). "Microbial degradation of marine plastics: Current state and future prospects," in *Biotechnol. Sustain. Environ.* Editors S. J. Joshi, A. Deshmukh, and H. Sarma (Singapore: Springer Singapore), 111–154. doi:10.1007/978-981-16-1955-7_5

Van Cauwenberghe, L., and Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environ. Pollut.* 193, 65–70. doi:10.1016/j.envpol.2014.06.010

Van Sebille, E., Aliani, S., Law, K. L., Maximenko, N., Alsina, J. M., Bagaev, A., et al. (2020). The physical oceanography of the transport of floating marine debris. *Environ. Res. Lett.* 15, 023003. doi:10.1088/1748-9326/ab6d7d

Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B. D., Van Franeker, J. A., et al. (2015). A global inventory of small floating plastic debris. *Environ. Res. Lett.* 10, 124006. doi:10.1088/1748-9326/10/12/124006

Viršek, M. K., Lovšin, M. N., Koren, Š., Kržan, A., and Peterlin, M. (2017). Microplastics as a vector for the transport of the bacterial fish pathogen species Aeromonas salmonicida. *Mar. Pollut. Bull.* 125, 301–309. doi:10.1016/j.marpolbul.2017.08.024

Vithanage, M., Ramanayaka, S., Hasinthara, S., and Navaratne, A. (2021). Compost as a carrier for microplastics and plastic-bound toxic metals into agroecosystems. *Curr. Opin. Environ. Sci. Health* 24, 100297. doi:10.1016/j.coesh.2021.100297

Wakkaf, T., El Zrelli, R., Kedzierski, M., Balti, R., Shaiek, M., Mansour, L., et al. (2020). Characterization of microplastics in the surface waters of an urban lagoon (bizerte lagoon, southern Mediterranean Sea): composition, density, distribution, and influence of environmental factors. *Mar. Pollut. Bull.* 160, 111625. doi:10.1016/j.marpolbul.2020.111625

Wang, J., Wang, M., Ru, S., and Liu, X. (2019). High levels of microplastic pollution in the sediments and benthic organisms of the south yellow sea, China. *Sci. Total Environ.* 651, 1661–1669. doi:10.1016/j.scitotenv.2018.10.007

Wang, S., Chen, H., Zhou, X., Tian, Y., Lin, C., Wang, W., et al. (2020). Microplastic abundance, distribution and composition in the mid-west Pacific Ocean. *Environ. Pollut.* 264, 114125. doi:10.1016/j.envpol.2020.114125

Wang, X., Xing, Y., Lv, M., Zhang, T., Ya, H., and Jiang, B. (2022). Recent advances on the effects of microplastics on elements cycling in the environment. *Sci. Total Environ.* 849, 157884. doi:10.1016/j.scitotenv.2022.157884

Waring, R. H., Harris, R. M., and Mitchell, S. C. (2018). Plastic contamination of the food chain: a threat to human health? *Maturitas* 115, 64–68. doi:10.1016/j.maturitas.2018.06.010

Wieczorek, A. M., Croot, P. L., Lombard, F., Sheahan, J. N., and Doyle, T. K. (2019). Microplastic ingestion by gelatinous zooplankton may lower efficiency of the biological pump. *Environ. Sci. Technol.* 53, 5387–5395. doi:10.1021/acs.est.8b07174

Woodall, L. C., Sanchez-Vidal, A., Canals, M., Paterson, G. L. J., Coppock, R., Sleight, V., et al. (2014). The deep sea is a major sink for microplastic debris. *R. Soc. Open Sci.* 1, 140317. doi:10.1098/rsos.140317

World Bank (2023a). Fiji GDP and GDP data.

World Bank (2023b). Ecuador GDP data.

World Bank (2023c). Peru GDP data.

Worm, B., Lotze, H. K., Jubinville, I., Wilcox, C., and Jambeck, J. (2017). Plastic as a persistent marine pollutant. *Annu. Rev. Environ. Resour.* 42, 1–26. doi:10.1146/annurev-environ-102016-060700

Wright, S. L., and Kelly, F. J. (2017). Plastic and human health: a micro issue? *Environ. Sci. Technol.* 51, 6634–6647. doi:10.1021/acs.est.7b00423

Wright, S. L., Rowe, D., Thompson, R. C., and Galloway, T. S. (2013). Microplastic ingestion decreases energy reserves in marine worms. *Curr. Biol.* 23, R1031–R1033. doi:10.1016/j.cub.2013.10.068

Wright, R. J., Erni-Cassola, G., Zadjelovic, V., Latva, M., and Christie-Oleza, J. A. (2020). Marine plastic debris: a new surface for microbial colonization. *Environ. Sci. Technol.* 54, 11657–11672. doi:10.1021/acs.est.0c02305

Wright, R. J., Langille, M. G. I., and Walker, T. R. (2021). Food or just a free ride? A meta-analysis reveals the global diversity of the plastisphere. *ISME J.* 15, 789–806. doi:10.1038/s41396-020-00814-9

Wu, X., Pan, J., Li, M., Li, Y., Bartlam, M., and Wang, Y. (2019). Selective enrichment of bacterial pathogens by microplastic biofilm. *Water Res.* 165, 114979. doi:10.1016/j.watres.2019.114979

Wu, H., Hou, J., and Wang, X. (2023). A review of microplastic pollution in aquaculture: sources, effects, removal strategies and prospects. *Ecotoxicol. Environ. Saf.* 252, 114567. doi:10.1016/j.ecoenv.2023.114567

Xiong, S., Bai, G., Shen, X., and Zhou, Y. (2025). On microplastics abundance in waters of Guizhou, China. *J. Oceanol. Limnol.* 43, 383–395. doi:10.1007/s00343-025-4207-0

Yang, Y., Liu, W., Zhang, Z., Grossart, H.-P., and Gadd, G. M. (2020). Microplastics provide new microbial niches in aquatic environments. *Appl. Microbiol. Biotechnol.* 104, 6501–6511. doi:10.1007/s00253-020-10704-x

Yin, L., Wen, X., Huang, D., Zeng, G., Deng, R., Liu, R., et al. (2021). Microplastics retention by reeds in freshwater environment. *Sci. Total Environ.* 790, 148200. doi:10.1016/j.scitotenv.2021.148200

Yose, P., Thondhlana, G., and Fraser, G. (2023). Conceptualizing the socio-cultural impacts of marine plastic pollution on human well-being – a perspective. *Mar. Pollut. Bull.* 194, 115285. doi:10.1016/j.marpolbul.2023.115285

Yu, H., Qi, W., Cao, X., Hu, J., Li, Y., Peng, J., et al. (2021a). Microplastic residues in wetland ecosystems: do they truly threaten the plant-microbe-soil system? *Environ. Int.* 156, 106708. doi:10.1016/j.envint.2021.106708

Yu, Y., Mo, W. Y., and Luukkonen, T. (2021b). Adsorption behaviour and interaction of organic micropollutants with nano and microplastics – a review. *Sci. Total Environ.* 797, 149140. doi:10.1016/j.scitotenv.2021.149140

Yuan, D., Corvianawatie, C., Cordova, M. R., Surinati, D., Li, Y., Wang, Z., et al. (2023). Microplastics in the tropical northwestern Pacific Ocean and the Indonesian seas. *J. Sea Res.* 194, 102406. doi:10.1016/j.seares.2023.102406

Zarfl, C., and Matthies, M. (2010). Are marine plastic particles transport vectors for organic pollutants to the arctic? *Mar. Pollut. Bull.* 60, 1810–1814. doi:10.1016/j.marpolbul.2010.05.026

Zbyszewski, M., Corcoran, P. L., and Hockin, A. (2014). Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. *J. Gt. Lakes Res.* 40, 288–299. doi:10.1016/j.jglr.2014.02.012

Zettler, E. R., Mincer, T. J., and Amaral-Zettler, L. A. (2013). Life in the “plastisphere”: microbial communities on plastic marine debris. *Environ. Sci. Technol.* 47, 7137–7146. doi:10.1021/es401288x

Zhang, C., Chen, X., Wang, J., and Tan, L. (2017). Toxic effects of microplastic on marine microalgae skeletonema costatum: interactions between microplastic and algae. *Environ. Pollut.* 220, 1282–1288. doi:10.1016/j.envpol.2016.11.005

Zhang, F., Wang, X., Xu, J., Zhu, L., Peng, G., Xu, P., et al. (2019). Food-web transfer of microplastics between wild caught fish and crustaceans in East China Sea. *Mar. Pollut. Bull.* 146, 173–182. doi:10.1016/j.marpolbul.2019.05.061

Zhang, L., Xie, Y., Liu, J., Zhong, S., Qian, Y., and Gao, P. (2020). An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. *Environ. Sci. Technol.* 54, 4248–4255. doi:10.1021/acs.est.9b07905

Zhang, C., Wang, Q., Wang, S., Pan, Z., Sun, D., Cheng, Y., et al. (2021a). Effects of virgin microplastics on growth, intestinal morphology and microbiota on largemouth bass (*Micropterus salmoides*). *Appl. Sci.* 11, 11921. doi:10.3390/app112411921

Zhang, X., Wen, K., Ding, D., Liu, J., Lei, Z., Chen, X., et al. (2021b). Size-dependent adverse effects of microplastics on intestinal microbiota and metabolic homeostasis in the marine medaka (Oryzias melastigma). *Environ. Int.* 151, 106452. doi:10.1016/j.envint.2021.106452

Zhang, P., Liu, Y., Zhang, L., Xu, M., Gao, L., and Zhao, B. (2022). The interaction of micro/nano plastics and the environment: effects of ecological Corona on the toxicity to aquatic organisms. *Ecotoxicol. Environ. Saf.* 243, 113997. doi:10.1016/j.ecoenv.2022.113997

Zhang, Y., Wu, P., Xu, R., Wang, X., Lei, L., Schartup, A. T., et al. (2023). Plastic waste discharge to the global ocean constrained by seawater observations. *Nat. Commun.* 14, 1372. doi:10.1038/s41467-023-37108-5

Zhang, H., Huang, Y., Shen, J., Xu, F., Hou, H., Xie, C., et al. (2024). Mechanism of polyethylene and biodegradable microplastic aging effects on soil organic carbon fractions in different land-use types. *Sci. Total Environ.* 912, 168961. doi:10.1016/j.scitotenv.2023.168961

Zhang, K., Zheng, S., Zhao, C., Liang, J., and Sun, X. (2025). Bioturbation effects and behavioral changes in buried bivalves after exposure to microplastics. *J. Hazard Mater* 484, 136765. doi:10.1016/j.jhazmat.2024.136765

Zhao, S., Zettler, E. R., Amaral-Zettler, L. A., and Mincer, T. J. (2021). Microbial carrying capacity and carbon biomass of plastic marine debris. *ISME J.* 15, 67–77. doi:10.1038/s41396-020-00756-2

Zhao, K., Wei, Y., Dong, J., Zhao, P., Wang, Y., Pan, X., et al. (2022a). Separation and characterization of microplastic and nanoplastic particles in marine environment. *Environ. Pollut.* 297, 118773. doi:10.1016/j.envpol.2021.118773

Zhao, Q., Chen, X., Chen, G., and Qi, S. (2022b). Understanding the development of recreational fisheries with an industry competitiveness framework: evaluation of a case study from China. *Mar. Policy* 143, 105121. doi:10.1016/j.marpol.2022.105121

Zhaorong, M., Yousheng, L., Qianqian, Z., and Guangguo, Y. (2020). The usage and environmental pollution of agricultural plastic film. *Asian J. Ecotoxicol.*, 21–32.

Zheng, J., and Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nat. Clim. Change* 9, 374–378. doi:10.1038/s41558-019-0459-z

Zhou, X., Xiao, C., Li, X., Chen, T., and Yang, X. (2023). Microplastics in coastal blue carbon ecosystems: a global meta-analysis of its distribution, driving mechanisms, and potential risks. *Sci. Total Environ.* 878, 163048. doi:10.1016/j.scitotenv.2023.163048

Zhu, C., Li, Y., Liu, G., Abdullah, A. L., and Jiang, Q. (2024). Effects of nanoplastics on the gut microbiota of Pacific white shrimp *litopenaeus Vannamei*. *PeerJ* 12, e16743. doi:10.7717/peerj.16743

Ziajahromi, S., Neale, P. A., Rintoul, L., and Leusch, F. D. L. (2017). Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. *Water Res.* 112, 93–99. doi:10.1016/j.watres.2017.01.042

Ziani, K., Ioniță-Mîndrican, C.-B., Mititelu, M., Neacşu, S. M., Negrei, C., Moroşan, E., et al. (2023). Microplastics: a real global threat for environment and food safety: a state of the art review. *Nutrients* 15, 617. doi:10.3390/nu15030617

Zitouni, N., Bousserrhine, N., Missawi, O., Boughattas, I., Chèvre, N., Santos, R., et al. (2021). Uptake, tissue distribution and toxicological effects of environmental microplastics in early juvenile fish dicentrarchus labrax. *J. Hazard Mater* 403, 124055. doi:10.1016/j.jhazmat.2020.124055