Chapter 6

Microplastics in the Marine Environment: A Review of Their Sources, Formation, Fate, and Ecotoxicological Impact

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Abstract

Global plastic production is on the rise, and improper plastic management leads to the disposal of plastic in the environment, wherein it enters the environment, after degradation, as microplastics (size < 5 mm) and nanoplastics (size < 1 μm). The most common sink for the microplastics is the marine environment, including the sediment, deep sea, shorelines, and oceans. The objective of this study is to collate the environmental impact assessment of the microplastics in the marine habitat, focusing on the following main elements: (a) source and type of microplastics, specifically leading to the marine sink; (b) degradation pathways; (c) ecotoxicological impact on marine biota, since the smaller-sized microplastics can be digested by the marine biota and cause threats to them; (d) fate of microplastic in the marine environment, including the modes of transport and deposition. This chapter aims to provide a deeper insight into the fate of microplastics once it enters the marine environment, and the information could be a useful reference for the development of microplastic risk management strategies.

Keywords: microplastics, plastic waste, marine habitat, ecotoxicology, degradation

1. Introduction

Global plastic production is on the rise wherein 1.3 million tons of plastics were produced in 1950, and 359 million tons of plastic waste were generated in 2018 [1, 2]. It is estimated that the increase in plastic waste will reach 250 million metric tons by 2025 [3]. This adds additional pressure on the plastic management system. At present, 9% of the plastic waste is recycled, 50% ends up in landfills, 19% is incinerated, and the remaining 22% ends up being discarded as litter (and is categorized as mismanaged plastic waste) [4, 5]. The mismanaged plastic waste is often dumped on terrestrial lands or in marine habitats [6]. It has been estimated that 10% of the mismanaged plastic waste ends up in the marine environment where it will persist and accumulate over the coming years [7]. The large fragments of plastic debris found

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in the environment are termed macroplastics [8], and they are known to harm turtles and sea birds via entanglement [9, 10].

Once these macroplastics enter the environment, they undergo degradation and decompose into smaller fragments known as microplastics (size < 5 mm) and/or nanoplastics (size < 1 μm) [11, 12]. Microplastics can be differentiated into primary microplastics and secondary microplastics, depending on their sources. Primary microplastics are the ones manufactured for direct applications such as microbeads in personal skin care products [13–15]. Secondary microplastics are the ones formed as a result of the degradation and decomposition of the macroplastics [16]. The most common sink for microplastics is the marine environment, including the sediment, deep sea [17, 18], shorelines [19, 20], oceans [21, 22], and interestingly coral reefs as well [23].

Globally, microplastics are recognized as pollutants, and the United Nations Sustainable Development Goals (UN SDG) has assigned Goal 14 specifically to conserve and sustainably use the oceans, seas, and marine resources [24]. The contamination by microplastics and nanoplastics has been an issue of concern over the past decade. Owing to their small size, micro/nano plastics are readily bioavailable for consumption by marine organisms [25]. Once ingested by smaller marine organisms (primary consumers), they will be further transferred to the secondary consumers (e.g., large fishes) and eventually reach the tertiary consumers (e.g., humans), thus disrupting the food chain [26].

Though the sources, degradation pathways, and sinks (specifically marine habitat) of the microplastics are often discussed, the fate of microplastics is elusive after perusing various articles and literature. Through this chapter, we aim to collate the environmental impact assessment of the microplastics in the marine habitat, focusing on the following main elements: (a) sources of microplastics, their transport to the marine environment, as well as their types; (b) degradation pathways including photodegradation, weathering, corrosion, or mechanical forces of water; (c) ecotoxicological impact on marine biota, since the fragmented microplastics can be readily digested by the marine biota and cause a threat to them; (d) fate of microplastic in the marine environment, including the modes of transport and deposition. This chapter aims to provide a platform for the development of microplastic risk management strategies and also to provide a deeper insight into the fate of microplastics once it enters the marine environment.

2. Sources, transport, and type of microplastics

In this section, we examine the main sources of microplastics, followed by how they reach the marine environment. Lastly, the types of microplastics predominant in the marine ecosystem are summarized.

2.1 Sources of microplastics

The sources of microplastics can be categorized into primary and secondary sources, and each category is discussed as follows.

2.1.1 Primary sources

Primary sources of microplastics include: **plastic pellets**, also known as nibs (diameter: 2–5 mm), which are used to make various types of plastic products [27];

microbeads, which are used in the manufacturing of personal care products, face wash, face cleansers, facial scrubs, hair products, nail polish, deodorants, sunscreen, and eye shadows [13–15]; **glitters,** which are shiny substances found in cosmetics and textile products. They are usually made of polyethylene terephthalate (PET) polymer, acrylic, polyvinyl chloride (PVC), and/or polymethyl methacrylate (PMMA) [28]. These primary plastics vary in shape, size, and composition depending upon their applications [15]. For example, certain cosmetic products contain granules of polyethylene and polypropylene (<5 mm), spheres of polystyrene (<2 mm) [29], or irregularly shaped microplastics (<0.5 mm) [15]. Apart from cosmetics, these primary sources of microplastics also find applications in air-blasting technology [14, 29]. This technology uses acrylic, melamine, or polyester as scrubbers at high pressure on machines, engines, and water vessel hulls to scrape off rust buildup or paint [13, 30].

2.1.2 Secondary sources

2.1.2.1 Effluent from water and wastewater treatment plants

Water and wastewater treatment plants are one of the main sources of releasing microplastics into the marine environment [31]. They are found in the primary stages of water treatment. Because of their small size, they can pass through the filters and enter the secondary units [32]. Microplastics detected in the influents ranged from ~1 to 10,000 particles per liter, and after treatment, microplastics in the effluent ranged from ~0 to 450 particles per liter (as summarized by a number of studies reviewed by Sun et al. [33]). Microfibers, including polyester, acrylic, and polyamide, are detected in the effluent of wastewater treatment plants [34], which implies the limitations of these treatment facilities to remove these microplastics.

2.1.2.2 Wear and tear from normal plastic use

The most common example of such a source type is the microplastic released as a result of washing clothes and textiles during laundry [35]. As a result, microplastics released from laundry activities eventually reach the marine environment. It is estimated that laundry activities are responsible for 500,000 tons of microplastics in the ocean per year [36, 37]. Apart from textiles/clothes weathering, use of fishing gears, including nets and ropes [38], wear and tear of car tires [39], as well as weathering of household items, including toys, plastics wares, and plastic disposables items [40].

2.1.2.3 Airborne dust

Plastic dust is released from a number of activities including plastic manufacturing facilities, incineration of plastic wastes, traffic emissions, weathering of roads and streets, and urban mining activities [41, 42]. Airborne dust is carried by wind and can settle in indoor settings including schools and houses [43, 44]. In houses, airborne microplastic comes from plastic items used in household items including food packaging, plastic wear, and plastic furnishings [45]. Most recently, during the COVID-19 pandemic, the requirement to wear face masks was made mandatory to prevent the spread of coronavirus. The surgical facemasks were made up of PP, PE, PS, and polyester. Studies showed that wearing these masks exposed the humans directly to inhalation of micro (<1 μm) and nanofibers (<100 nm) [46–48].

2.1.2.4 Secondary microplastics

Primary microplastics may also contribute to the secondary sources of microplastics. Once exposed to the environment, plastic wastes and primary sources of microplastics undergoes weathering and degradation to form secondary microplastics [12]. Details on the degradation process of plastic waste are given in Section 3. Plastic litters including disposable plastic cutlery, plastic cups, food containers, as well as face masks in the era of COVID-19 pandemic (that started in 2019 and is still ongoing in the current year of 2022) end up being dumped on coastal shorelines, where they undergo further degradation and decomposition [48–50].

2.2 Transport

There are four main pathways through which microplastics from different sources reach the marine environment: (a) as surface runoff when the plastic wastes are thrown on the terrestrial lands and eventually travel along with the runoff due to rainfall. Transport via surface runoff is responsible for 44% of the total microplastics being released into the marine ecosystem; (b) via wind, which transports the plastic waste on the terrestrial zone to seas/oceans along with the atmospheric currents. Transport via wind is responsible for 15% of the total microplastics being released into the marine ecosystem; (c) as wastewater discharge in which microplastics can enter the receiving water bodies and is responsible for 37% of the total microplastics released; (d) and lastly, through direct disposal of plastic wastes into the marine environment, which is responsible for 4% of the total microplastics release [7, 13, 30, 51]. Direct disposal of plastic wastes activities includes washing clothes in the rivers, usually in the rural areas [52], coastal tourism activities including fishing and recreational activities resulting in disposable cups and litters [53], and commercial fishing resulting in nets and litters [54].

2.3 Types of microplastics

Microplastics can be categorized into primary and secondary microplastics depending on their sources, as discussed in Sections 1 and 2.1. Depending on their density and chemical compositions, microplastics can be classified into different types including polystyrene (PS), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and others (e.g., nylon, polyester) [55, 56]. The different plastic types, properties, and functions where these plastics are commonly used are given in **Table 1**. Microplastics can also be differentiated on the basis of shape: pellets, microbeads, foams, fibers, films, fragments, and microfibers (**Figure 1**) [57].

3. Degradation pathways

Plastic wastes undergo environmental weathering resulting in the formation of microplastics or even smaller fragments of nanoplastics. These degradation pathways can be classified into abiotic and biotic processes [62–64].

Plastic type	Abbreviation	Properties	Common applications
Polystyrene	PS	Density (1.04–1.08 g/cm^3) transparent, hard.	Personal care products (as microbeads), household items (utensils and containers), disposable cups, plastic components of electronic instruments, and packaging.
Low-density polyethylene	LDPE	Density (0.89–0.94 g/cm^3), translucent, soft.	Clingy plastic wraps and films, containers, plastic bags, and flexible pipes and tubing.
High-density polyethylene	HDPE	Density (0.94–0.97 g/cm^3), opaque, hard/semi-flexible.	Food packaging (cereal box liners, milk bottles), freezer bags, plastic stools, courier envelopes, and toys.
Polypropylene	PP	Density (0.89–0.91 g/cm^3), translucent, hard.	Straws, packaging tapes, snack bags (chips and biscuit bags), fishing gears (nets and ropes), bottle caps, clothing, textiles, and microbeads in skin care products.
Polyvinyl chloride	PVC	Density (1.3–1.58 g/cm^3), transparent (clear), hard.	Medical supplies (blood bags, surgical gloves and face masks), building structures (floorings, roof plates, swimming tanks, and fittings), shoes, and tents.
Polyethylene terephthalate	PET	Density (1.29–1.4 g/cm^3), transparent, hard.	Food packaging (clamshell packaging in takeaway containers such as salad domes, biscuits and snack trays), thermal insulations, and textiles.
Others	Ex.:polyester, polyamide (nylon)	Density of polyester (1.01–1.46 g/cm^3), Density of polyamide (1.13–1.35 g/cm^3).	Packaging, nylon products, textiles, abrasives in cleaning supplies.

Table 1.
Properties and common applications of different types of plastic found in the marine environment [55, 56, 58–61].

3.1 Abiotic degradation pathway

Abiotic factors include mechanical forces that are responsible to damage the plastic wastes physically, temperature increase (thermal degradation), chemical degradation, and light irradiation (leading to photodegradation) [12].

3.1.1 Mechanical degradation

Mechanical degradation refers to the action of external forces caused by wind current, ocean waves, or physical wear and tear resulting in breakdowns of plastics [12]. Plastic litters on coastal shorelines are exposed to collision and abrasion with beach rocks and sands as a consequence of motion caused by wind and ocean circulations. In the colder zones, repetitive freezing and thawing of ice can cause the degradation of the plastics accumulated in the ice and eventually result in their flow back into the marine habitat [65, 66]. One example of mechanical degradation of plastic is wear

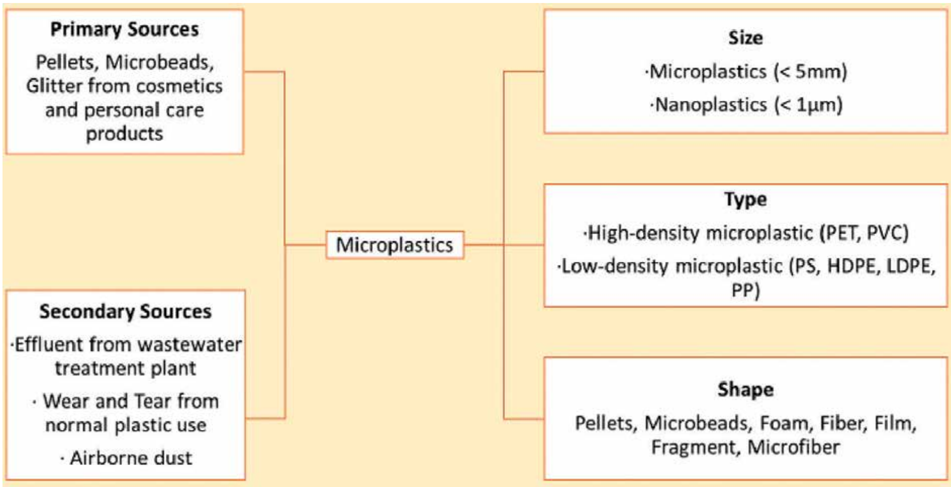

Figure 1.
Characterization of microplastics based on source, size, type, and shape.

and tear on the road as a result of friction caused by the moving car tires [67]. Tire, road, and brake wear happens because of the mechanical forces being exerted on the brake pads, tire threads, and the road surface, resulting in material stressing and fatigue [68].

3.1.2 Thermal degradation

Plastic waste litters on the coastal shorelines are exposed to elevated temperatures, leading to a thermo-oxidative breakdown of the plastic. Thermal degradation of plastics involves absorption of heat and breaking of polymeric chains thus releasing radicals that react with atmospheric oxygen to produce hydroperoxide, which eventually cleaves into hydroxyl and alkoxy free radicals. These radicals result in the formation of aldehydes, ketones, esters, or alcohols, causing plastic degradation [69]. Chain scission and cross-linking of the polymers are responsible for the thermal degradation process [70, 71]. In the environmental matrix related to beaches and coastal shorelines, slow thermal degradation of plastics may occur concurrently with photodegradation (due to the presence of sunlight), resulting in enhanced plastic degradation [72].

3.1.3 Chemical degradation

Chemical pollutants are present in the atmosphere (e.g., sulfur dioxide, nitrogen dioxide, ozone, and volatile organic compounds) and the marine environment (e.g., acidity and salinity). The atmospheric pollutants can directly degrade the plastics or catalyze the radical formation by photochemical reactions leading to plastic degradation [73]. Sulfur dioxide and nitrogen dioxide can enhance the formation of ozone in the atmosphere, as a result of UV excitation and photochemical reaction with oxygen [74]. The ozone formed can break the carbon double bonds present in the plastic polymers (chain scission mechanism). In the marine environment, the acidity or alkalinity of the water can catalyze plastic degradation such as polyamides [75].

3.1.4 Photodegradation

Photodegradation of plastic is mediated by sunlight UV radiations, both UVB (290–315 nm, high-energy radiation) and UVA (315–400 nm, medium-energy radiation) [12, 76]. Photodegradation of plastic involves free radical formation and oxidation of the plastic polymers, resulting in the formation of peroxides, which eventually breaks into alkoxy and hydroxyl radicals, similar to the thermal degradation mechanism. Photodegradation in the atmosphere results in the formation of free radicals to break different plastics depending on their chemical structures. For example, the presence of chromophores (alternating or conjugating carbon double bonds) in PP, PE, and PVC, phenyl rings in PS, and ethylene glycolate and terephthalate groups linked with ester bonds in PET mediate the free radical formation reactions as a result of photodegradation [12].

3.2 Biotic degradation pathway

Plastic degradation by microorganisms present in the marine habitat results in the biodegradation of plastic wastes. However, macroplastics (larger plastic debris) are not the ideal feedstock for biotic degrading agents owing to their size, which poses a hindrance to the degradation mechanism, either the enzymes produced by the microorganisms are not enough to degrade the macroplastics, or they are not readily bioavailable for microbial cell uptake. During the degradation process, polymeric plastics need to be first converted into monomers before they can be mineralized by the biological agents. The molecular size of plastics (i.e., polymers) is larger than the pore size of microorganism's cell membrane. Hence, they need to be depolymerized into smaller fragments before they can be absorbed and biodegraded within the microbial cells. Therefore, smaller fragments of plastic formed as a result of abiotic degradation are of the appropriate size to be further degraded by microorganisms [12]. Microorganisms predominantly present in the marine environment include bacteria, fungi, and algae.

3.2.1 Bacteria

Bacillus species are commonly found in the marine environment, for example, *Bacillus subtilis* and *Bacillus cereus.* These bacteria were found to secrete extracellular hydrolytic enzymes such as *lipase, xylanase, keratinase, chitinase, and protease*, which lead to plastic degradation [77]. PVC, the most common plastic polymer, can be degraded by *Methanosarcina barkei*. They can adhere to the surface of the PVC surfaces and release exopolymeric substances to form a biofilm on the PVC, followed by the release of enzymes to degrade the plastic via hydrolytic cleavage of the polymeric bonds [78, 79]. Similarly, PE can be degraded by *Rhodococcus ruber*, which produces an enzyme laccase that results in PE degradation [80]. PS can be degraded by *Azotobacter spp.*, which produces hydroquinone peroxidase. PET can be degraded by *Alcanivorax*, *Hyphomonas,* and *Cycloclasticus* species, which can change the surface chemistry via hydrolysis of the ester bonds [81].

3.2.2 Fungi

Fungi can also result in biotic degradation of plastics. For example, *Aspergillus clavatus* has been shown to biodegrade LDPE [82]. Oceans' predominant fungal species *Zalerion maritimum* can degrade PE [83]. Similar to bacteria, the main mechanism of plastic degradation by fungi involves the adherence of the fungi to the plastic surface, where they grow to form a biofilm and produce enzymes to break down the chemical bonds present in the plastic. These enzymes can catalyze oxidation-reduction reactions and break down plastic into smaller fragments (e.g., oligomers, dimers, and monomers). For example, manganese peroxidase, lignin peroxidase, and laccase are produced by fungi present in marine habitats, such as *Penicillium citrinum* (degrades PET), *Fusarium oxysporum* (degrades PET), and *Trichoderma harzianum* (degrades PE and PU) [83].

3.2.3 Algae

Some algae have been shown to produce secondary metabolites that can biodegrade microplastics. For example, *Phormidium lucidum* and *Oscillatoria subbrevis* can biodegrade PE and LDPE [84]. Algal biofilms formed by *Discostella spp.*, *Navicula spp.*, *Amphora spp.*, and *Fragilaria spp.* have shown to degrade LDPE, PP, and PET in the marine environment [85]. Once forming a biofilm on the plastic surface, algae utilize the carbon present on the plastic as a source of nutrition, thus weakening the strength of the plastic and making it fragile. Moreover, algae produce extracellular polymeric substances and enzymes such as PETase that result in the degradation of PET [86]. Plastic degradation by algae is still in its nascent phase and needs further research.

4. Distribution and fate of microplastic

The distribution and fate of the degraded plastic and microplastic in the marine system are attributed to anthropogenic activities (e.g., tourism, wastewater treatment effluent) in the form of primary microplastics [87]. Environmental factors lead to the introduction of secondary microplastics into the marine habitat, as discussed in Section 3. For example, the wastewater treatment plant effluent releases ~7 million microplastic particles every day [87, 88]. Hence, the marine environment serves as the primary sink for microplastics. Once into the marine system, their accumulation and distribution depend on a number of parameters pertaining to microplastics (e.g., density, size, shape, and chemical composition) and environment (e.g., wind and ocean current speed) [89, 90]. The fate of microplastics is related to their immediate source of disposal, and they can be translocated to remote areas such as artic seas and ice-capped regions [91]. Depending on the density of the microplastics, they can either remain suspended in the surface water or sink into the deep sediments. The density and other chemical properties of the most common types of microplastics are given in **Table 1**. If the density of the microplastic is lesser than that of the seawater (usually ~1.025 g/cm^3) [61], the microplastic may remain suspended in surface water and would be transported to distant locations through horizontal distribution driven by ocean circulations (Section 4.1). If the density of the microplastic is greater than that of the seawater, the microplastic may sink to the sea floor through a pathway of vertical distribution (Section 4.2) [61, 92, 93]. Data show that around 15% of microplastics remain in the suspended form, whereas 70% of microplastics accumulate in sea sediments [94]. In the United States, ~260 tons of PET are released from the used containers of personal care products alone, and this contributes to 25% of microplastics in the North Atlantic Ocean gyre [95]. Due to the variation in degradation mechanisms of different plastics, the continuous generation of plastic waste, and the dynamic nature of the environmental conditions (since the velocities of wind and ocean circulation vary along with the changing weather conditions), the fate of microplastic is not constantly steady and difficult to predict. This necessitates a proper understanding of the distribution of the microplastics once it enters the marine system.

4.1 Horizontal distribution

Coastal current, rainfall, and wind are responsible for the movement of the plastics from the coastal shorelines/beaches into the marine system [96–98]. Once the macroplastics enter the marine environment, they can undergo further degradation as a result of ocean abrasion or biotic degradation, as discussed in Section 3. The fate of the microplastics, those carried from the terrestrial shorelines and/or formed as the result of degradation in the marine system, depends on their intrinsic properties and ambient conditions. Depending on the velocity and direction of flow of the regional wind and water current, these microplastics can either be transported to remote regions or return to the coastal shorelines/beaches [32, 87, 99], resulting in the accumulation of microplastics in the oceanic/regional water gyres in the marine environment. Meanwhile, 5–13 million tons of plastic debris enter the ocean (data for 2010) [3], and approximately 7–35 thousand tons of suspended microplastics remained in the ocean surface water [100]. This implies that the remaining plastic debris was translocated (either by horizontal or vertical distribution pathways). **Figure 2** shows the distribution pathways for plastic and microplastics in the marine environment.

4.2 Vertical distribution

As stated previously, microplastics with density greater than that of the marine/region water may sink to the seabed. This process is mediated by vertical turbulent mixing, biota transfer (via fishes or other marine organisms), biological fouling (also known as biofouling), and aggregate formation [61, 101]. Biofouling is the accumulation of existing marine microorganisms, planktons, algae, microalgae, and small marine organisms on the plastic debris/microplastics [102]. This process depends on the polymer type, surface area, and size of the microplastic, as well as the microorganisms present in the marine environment, temperature, salinity, pH, nutrient/metals, and oxygen concentration of the water [66, 103–106]. For example, the presence of a plethora of bacterial species (*Alteromonas, Zoogloea, Ruegeria, Roseobacter, Nautella, and Pseudomonas*) in the benthic (6 m in depth) and the planktonic (2 m in depth) zones of the Arabian Gulf resulted in the biofouling of PET and PE [107]. Another study showed that the water conditions, primarily oxygen concentration and the presence of iron in the water resulted in biofouling of PET, PE, and PS by cyanobacteria, bacteria, and algae [108]. Biofouling starts with the attachment of the organisms, nutrients, flocculants, and dissolved organic compounds on the microplastic surface [109]. Subsequently, extracellular polymeric substances are released by the microorganisms to form a biofilm, which further attracts other marine invertebrates and worms [110]. As a result, the aggregate forms, the overall density of the microplastic increases, and it eventually sinks.

The density of marine water varies at different depths. Therefore, depending on the density of the aggregate formed, different layers can serve as a sink to accumulate microplastics [102]. Heavier aggregates can sink into the deep oceanic layers. The fate of the microplastics accumulated in the marine sediments is affected by the

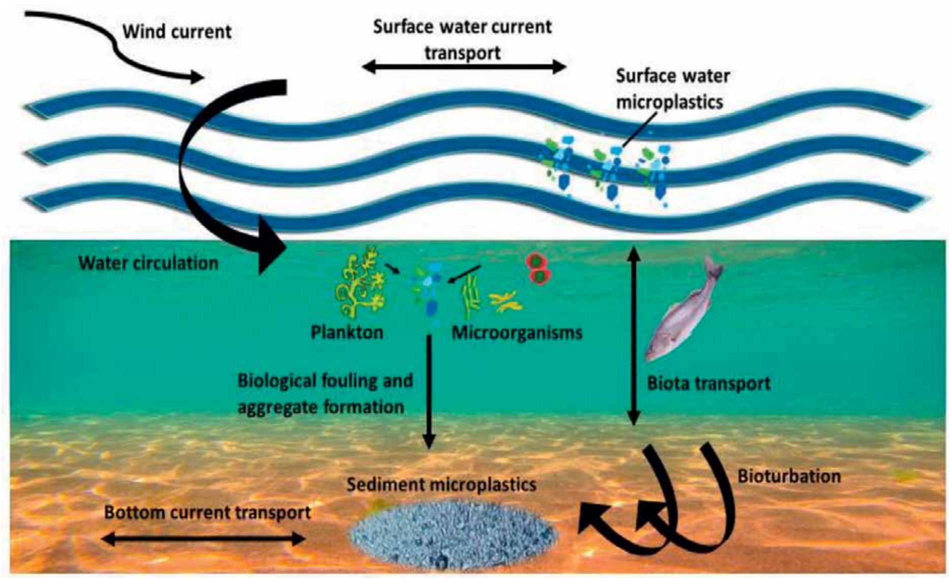

Figure 2.
Distribution pathways and fate of microplastics in the marine environment.

disturbance in the sediment zone, resulting in releasing the accumulated microplastics back into the water zone [111]. Also, similar to surface water currents, bottom water currents can also lead to the transportation of the microplastic to remote regions (**Figure 2**) [101].

5. Ecotoxicological impact on marine biota

Owing to their small size, microplastics have the potential to be ingested by an array of marine biota [112]. There are several studies indicating the ingestion and accumulation of microplastics in marine organisms, and most of the studies were conducted on fishes. **Table 2** lists a number of studies demonstrating the impact of microplastics on different marine organisms, categorized into fishes, invertebrates, and other miscellaneous biota. These studies indicated the accumulation of microplastics in various marine organisms including fishes (mackerel, *Scomber japonicus*), copepods (*Calanus helgolandicus*), and shorebirds (whimbrel, *Numenius phaeopus*), and pacific golden plover (*Pluvialis fulva*) [113–115]. When a microplastic accumulates in the organism's body tissues, it may influence the organism's health in numerous ways, including stunted growth, infertility, and impact on egg's hatching [114, 116]. Once ingested by the marine organisms, the microplastics can translocate through the food chain, starting from the primary consumers (e.g., planktons, small fishes), to the secondary (e.g., larger fishes, birds, turtles), and eventually to the tertiary ones (humans) [117]. Such a process is known as biomagnification, which may cause human health risks [32]. Moreover, microplastics can bind to various marine pollutants such as heavy metals, enhancing their accumulation in the marine environment [118]. In addition, marine invertebrates such as mollusks (e.g., mussels, oysters, clams) and crustaceans (e.g., shrimps, crabs, lobsters) do not possess the required digestive enzymes to break down the microplastics into simpler nontoxic compounds. Therefore, these invertebrates would release the microplastics back into the water as fecal matters [119]. As a result, the microplastic might not have any toxic impact on the marine organisms once the ingested microplastics are egested. In certain cases, microplastics can act as a vector of co-pollutants present in the marine system and prevent its translocation to the marine organisms, thus exhibiting a positive impact on the organism. For example, in the presence of co-pollutant (zinc oxide) and microplastics (PE), marine microalgae (*Dunaliella salina*) showed higher growth than in the absence of PE. This is because PE could attach to zinc oxide, leading to its leaching and preventing its uptake by the microalgae [120]. The ecotoxicological risk and impact of microplastics on the marine environment can be categorized into physical, chemical, and biological damages. Physical damage to marine organisms includes gastrointestinal tract blockage and damage, leading to the organism's death and affecting the mortality rate [121]. Chemical damage includes the property of microplastics acting as carriers or vectors for pollutants such as heavy metals (e.g., Cr, Ni, Cd, Zn) that are eventually ingested by marine organisms [122]. For instance, PE was found to facilitate the sorption of chromium (Cr) in common Goby fish, which led to a decrease in acetylcholinesterase (AchE) enzyme activity and resulted in acute toxicity [123]. Lastly, biological damage to marine organisms includes gene manipulation and the evolution of microorganisms with antibiotic resistance genes and metal resistance genes [124]. However, more research is needed to confirm the impact of these damages on marine organisms.

Table 2 also summarizes the ultimate marine sinks for the microplastics. The marine organisms impacted by the microplastics are primarily present in the following major oceans: the Pacific ocean, Atlantic ocean, and Indian ocean. Pacific ocean serves as a marine sink to microplastic generated from the United States (e.g., California [125]) and South America (e.g., Peru and Chile coastlines and Northern Patagonia in Chile [126, 127]). These examples represent the East Pacific Ocean as the marine sink for microplastics, where the main sources of these microplastics include plastic manufacturing industries in the United States (e.g., California [125]), and textile industries and domestic washing of clothing in South America (e.g., Peru and Chile [126, 127]). Likewise, the West Pacific Ocean serves as a microplastic source for marine habitats including zebrafish, rotifers, copepods, shrimps, scallops, crinoids, (China [128–130], gastropods, bivalves, and crabs (Hongkong [131]), as well as seabirds and turtles (China [115, 132]). Based on recent studies summarized in **Table 2**, the main source of microplastic in the West Pacific Ocean is China. The increased consumption of plastic in China is directly linked to its high population (1.41 billion [133]), plastic manufacturing industries, and mismanaged plastic wastes [134].

Similarly, increased fishing activities, tourism, and high population are the main reasons for the microplastic source of the Indian Ocean, including India (primarily the high population of 1.38 billion [133]) and Thailand (primarily the tourism activities and fishing activities, [135]). The source of microplastic to the Atlantic Ocean is due to the increased amount of plastic waste generated (e.g., United Kingdom), and the mismanaged plastic waste that makes it to the ocean [134]. For example, the East Atlantic Ocean serves as a microplastic source to marine organisms including common goby (Iberian coast, [123]), different pelagic and demersal species in the English Channel (UK, France [136–138]), gilthead seabream and European seabass (Murcia, Spain, [139]), mussels (Port Quinn Cornwall, UK, [140]), copepod (English Channel, UK, [114]), insects (Italy, [141]), whale (the Netherlands, [142]), and otters (Norway, [143]). Similarly, for the West Atlantic Ocean, the United States, and South America serve as a microplastic sink/source for different marine organisms including

Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
Fishes				
Commercial fish (26 species)	Portugal coast, Atlantic Ocean	PP, PE, polyester, nylon, acrylic, rayon, and resins.	*Scomber japonicus* ingested the highest amount of microplastics, mainly fibers and fragments.	Neves et al. [113]
Common goby (*Pomatoschistus microps*)	Estuaries of Minho River and Lima River (North-West Iberian Coast), Atlantic Ocean	PE	Presence of microplastic along with heavy metal chromium (Cr) resulted in decrease in acetylcholinesterase (AchE) activity. This results in acute toxicity of the fish towards Cr.	Luís et al. [123]
Zebrafish (*Danio rerio*)	Tianjin Baseline ChromTech Research Centre (Tianjin, China), Pacific Ocean	PS	Microplastic accumulated in the gills, guts and liver of Zebrafish. This resulted in multiple toxic effects including inflammation, increase in enzyme activity (superoxide dismutase and catalase). This leads to creating imbalance of metabolic pathways.	Lu et al. [128]
Japanese medaka (*Oryzias latipes*)	Aquatic Health Program at UC Davis (California), Pacific Ocean	PE	Ingestion of microplastic lead to disruption of normal functioning of the endocrine system. Down regulation in genes expression of choriogenin (ChgH) in male and vitellogenin (VTgI) & estrogen receptor (ERα) were reported.	Rochman et al. [125]

Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
Five pelagic species (whiting *Merlangius merlangus*), blue whiting *Micromesistius poutassou*, Atlantic horse mackerel *Trachurus*, poor cod *Trisopterus minutus* and John Dory *Zeus faber)* Five demersal species (red gurnard *Aspitrigla cuculus*, Dragonet *Callionymus lyra*, redband fish *Cepola macrophthalma*, solenette *Buglossisium luteum*, and thickback sole *Microchirus variegates)*	English Channel (UK), Atlantic Ocean.	Polyamide, Rayon	37% of the fish examined (n = 504) had ingested MP, which causes mortality by choking or sub-lethal damage due to disruption of intestinal tissues.	Lusher et al. [136]
Silver barb (*Barbodes gonionotus)*	Malaysia, Indian Ocean.	PVC	During the first 4 days, there was no damage to the fish, but after prolonged exposure, intestinal damage occurred followed by increased trypsin and chymotrypsin activity.	Romano et al [151]
European sea bass (*Dicentrarchus labrax)*	Atlantic Ocean	PVC	Intestinal damage.	Peda et al. [152]
European sea bass (*D. labrax)* larvae	Marine farm Aquastream (France), Atlantic Ocean	PE	Injuries and ulceration in the intestines.	Mazurais et al. [137]
3 fish species (*Clupea harengus*, *Sardina pilchardus* and *Engraulis encrasicolus*)	English Channel, the Northwestern Mediterranean Sea and the Northeastern Atlantic (Bay of Biscay), Atlantic Ocean	PE, PP, PET	Reduced gill functioning	Collard et al. [138]
Goldfish *(*Carassius auratus*)*	Laboratory conditions	PS, PE	MPs were found in the gills, guts, and feces.	Jabeen et al. [148]

Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
European seabass (*D. labrax*), the Atlantic horse mackerel (*Trachurus trachurus*) and Atlantic chub mackerel (*Scomber colias*)	Northwest Portuguese coastal waters, Atlantic Ocean	PS, PE	MPs were ingested and caused neurotoxicity and oxidative damage.	Barboza et al. [144]
Discus fish (*Symphysodon aequifasciatus*)	Manacapuru Lake system (Amazon Basin, Brazil), Atlantic Ocean	PS	MP induced oxidative stress in combination with Cd contamination.	Wen et al. [145]
Fathead minnow (*Pimephales promela)*	Laboratory conditions	PS	MP suppresses the immunity in fish.	Greven et al. [149]
Gilthead seabream (*Sparus aurata*) and European sea bass (*D. labrax*)	Local farm (Murcia, Spain), Atlantic Ocean	PVC, PE	MP impacts the fish leukocytes and induce oxidative stress.	Espinosa et al. [139]
Marine medaka (*Oryzias melastigma*)	Laboratory conditions	PS	MP caused damage to reproduction.	Wang et al. [153]
Catfish *(Arius maculatus)*	Songkhla Lake, Thailand, Indian Ocean	Rayon, polyester, polyvinyl alcohol, PE, paint	Accumulation of MP in the stomach.	Pradit et al. [135]
Zebrafish (*D. rerio*) larvae	Laboratory conditions	PS	MP accumulated in the cardiovascular organs.	Veneman et al. [154]
Invertebrate				
Mussels (*Mytilus edulis*)	Port Quinn, Cornwall (UK), Atlantic Ocean	PS	Ingested PS accumulated in the circulatory fluid, and fecal matters contained PS.	Browne et al. [140]
Sea cucumbers (*Holothuroidea* spp.)	Panacea, Florida; Fort Pierce, Florida; and Walpole, Maine (USA), Pacific Ocean	PVC, Nylon	Ingestion of various sizes of PVC and nylon (up to 4 mm), depending on the opening of the tentacles. Poses a threat to primary consumers of sea cucumbers.	Graham and Thompson [146]
Oysters (*Ostrea edulis*)	Queen's University Marine Laboratory, Portaferry (Ireland), Atlantic Ocean	HDPE	Ingestion of HDPE resulted in greater respiration rates in oysters, effecting the mortality rate.	Green [155]

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Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
Copepod (*Calanus helgolandicus*)	English Channel (UK). Atlantic Ocean	PS	PS resulted in decreasing the reproduction rate, but no significant effect on egg production rate, survival rate, and respiration rate.	Cole et al. [114]
Shrimps (*Metapenaeus monoceros, Parapeneopsis stylifera*, and *Penaeus indicus*)	Fishing ground, Arabian Sea, Indian Ocean	PP, PE, polyamide, nylon, polyester, and PET	Microplastics accumulated in the gastrointestinal tract and gut. Shapes of microplastics detected were fiber, pellets, fragments, beads, and films.	Gurjar et al. [156]
Barnacle shrimp (*Amphibalanus amphitrite*) and brine shrimp (*Artemia franciscana*)	Cysts of the species were collected from laboratory from Italy and Belgium, Atlantic Ocean.	PS	MP increase the acetylcholinesterase activity in fish brains, leading to oxidative stress.	Gambardella et al. [157]
Marine copepod (*Tigriopus japonicus*)	Laboratory conditions	PP	MP ingestion and reduction in their fecundity.	Sun et al. [150]
Rotifers *(Brachionus rotundiformis),* Copepods (*Parvocalanus crassirostris*), Shrimp (*Penaeus vannamei*), Scallops (*Chylamys nobilis*)	Center for Collections of Marine Algae at Xiamen University (CCMA, Xiamen, China), Pacific Ocean	PP	MPs were found in the digestive tract.	Ma et al. [129]
Spear shrimp (*Parapenaeopsis hardwickii*), Yellow shrimp (*Metapenaeus brevicornis*)	Songkhla Lake, Thailand, Indian Ocean	Rayon, polyester, polyvinyl alcohol, PE, paint	Accumulation of MP in the stomach.	Pradit et al. [135]
Insects (*Trichoptera, Plecoptera*, and *Coleoptera*)	Vipacco/Vipava River (Friuli Venezia Giulia, northeast Italy, Atlantic Ocean	Polyester	MP accumulation in the invertebrates.	Bertoli et al. [141]
Gammaridae, Asellidae, Tubificidae, and *Chironomidae*	Lowland River (Belgium), Atlantic Ocean.	PE, PP, PVC, others	MP accumulation in the gut.	Pan et al. [158]
38 species of gastropods, bivalves, and crabs	Mudflats and sandy beaches (Hongkong), Pacific Ocean	PET, cellophane, polyamide	0–18 MP per organism was found.	Xu et al. [131]
Chironomids larvae	Lake Jinhu in Chongqing, China, Pacific Ocean	PE	MP lowered the nitrogen removal capability of the larvae.	Huang et al. [130]

Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
Aquatic larvae caddisfly (*Sericostoma pyrenaicum*)	Perea stream (Spain), Atlantic Ocean	PS	MP were found in the larvae feces, indicating MP ingestions and egestion.	López-Rojo et al. [159]
Marine copepod (*Pseudodiaptomus annandalei*)	Laboratory conditions	PS	MP ingested as well as egested.	Cheng et al. [160]
Sea urchins	Ría de Vigo (Galicia, NW Iberian Peninsula), Atlantic Ocean	PE	MP ingestion detected.	Beiras and Tato [161]
Copepods (*C. helgolandicus*, *Acartia tonsa*) and European lobster (*Homarus gammarus*)	Western Channel Observatory station (UK), Atlantic Ocean	PS, nylon	MP ingestion detected.	Botterell et al. [162]
Other miscellaneous marine biota				
Seabird (red-footed booby, *Sula sula*) and shorebirds (whimbrel, *Numenius phaeopus* and pacific golden plover *Pluvialis fulva*)	Yongxing Island, South China Sea, Western Pacific Ocean	PP-PE copolymer	Birds ingested the microplastics mistaking it for food items. This resulted in accumulation of microplastics in their stomach, esophagus, gastrointestinal tracts, and intestine. Microplastics consisted primarily of thread- shaped and blue-colored pieces.	Zhu et al. [115]
Dolphin (*Delphinus delphis*)	Galicia, Iberian Peninsula, Atlantic Ocean	Not determined	Microplastic accumulated in the stomach of dolphins, including fragments, beads, and fibers.	Hernandez-Gonzalez et al. [163]
Humpback whale (*Megaptera novaeangliae*)	Sandbank between Den Helder and Texel (Netherlands), Atlantic Ocean	PE, PP, PVC, PET, nylon	Various sizes of plastics (1 mm-17 cm) accumulated in the gastrointestinal tract. Shapes detected were sheets, fragments, and threads. Microplastic caused blockage of the intestinal tract, disrupting the digestion process.	Besseling et al. [142]

Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
Green turtle (*Chelonia mydas*)	Hainan Island (China), North Pacific Ocean	PS, PE	Presence of microplastics in the beach sand resulted in disruption of the nesting ground for turtle and delay in egg hatching,	Zhang et al. [132]
Green algae (*Cladophora* spp.)	Lakes Michigan and Erie (Laurentian Great Lakes), Atlantic Ocean.	PE, PET, Spandex	Cladophora readily sequestered the microplastics from the water. This in return would lead to trophic transfer when these algae will be consumed by other marine organisms.	Peller et al. [164]
Marine diatoms (*Phaeodactylum tricornutum*)	Center for Collections of Marine Algae at Xiamen University (CCMA, Xiamen, China), Pacific Ocean	PP	MP impacts the photosynthesis ability of the algae.	Ma et al. [129]
Algae (*Skeletonema costatum*)	Laboratory conditions	PE, PS, PVC	Microalgae growth decreased with increasing MP concentration.	Zhu et al. [165]
Marine microalgae (*Dunaliella salina*)	Laboratory conditions. Microalgae were procured from Tamil Nadu (India), Indian Ocean.	PS	Low concentration of MP resulted in lowering the toxic impact of co-pollutant (zinc oxide) on microalgae.	Gunasekaran et al. [166]
Marine microalgae (*D. salina*)	Laboratory conditions. Microalgae were procured Library of Marine Samples, Korea Institute of Ocean Science & Technology (KIOST, Geoje, Korea).	PE	In the presence of co-pollutants, MP can remove and leach these pollutants and henceforth enhance the growth of microalgae.	Chae et al. [120]
Walrus (*Odobenus rosmarus*)	Svalbard coastline, Arctic Ocean	PE, PP, polyamide, polyester, acrylic	MP detection in the walrus feces.	Carlsson et al. [167]
Eared Seal (3 species of otariids: *Arctocephalus australis, Arctocephalus phillippii*, *Otaria byronia*)	Peru and Chile coastlines, Pacific Ocean	PET, nylon	MP detected in seals.	Perez-Venegas et al. [127]

Organisms	Sample location, major ocean sink	Type of MP	Impact	Reference
Beluga whales (*Delphinapterus leucas*)	Hendrickson Island, Northwest Territories (Canada), Pacific and Arctic Ocean	PVC, PP, nylon, polyolefin, PET, polyester	MPs were detected in the gastrointestinal tract.	Moore et al. [168]
Otters (*Lutra lutra*)	West Coast of Norway, Atlantic Ocean	PVC, PS, PET	MPs were detected in the stomach of the otters.	Haave et al. [143]
Fur Seals (*A. australis*)	Chilean Northern Patagonia, Pacific Ocean	Microfibers (Type of MP not determined)	MP detected in the seal's feces.	Perez-Venegas et al. [126]
Harbor seal (*Phoca vitulina vitulina*) and Gray seal (*Halichoerus grypus atlantica*)	Cape Cod, Massachusetts, USA, Atlantic Ocean	Resin, Cellophane, PET, PP	MP detected in the fecal samples.	Hudak and Sette [147]
Harbor porpoises (*Phocoena phocoena*)	Netherlands, Atlantic Ocean	PE, PP, PVC, Polyamide, PET	MP detected in the stomach.	Van Franeker et al. [169]

Table 2.
Impact of microplastic (MP) on various marine biota. Please note that for the laboratory simulated studies, the major ocean sink information has not been included.

commercial fishes, seabass, and mackerel found along the Portugal coast ([113, 144]), discus fish found in the Amazon basin, Brazil [145], sea cucumbers in Florida and Maine (the USA, [146]), and seals in Massachusetts (the USA, [147]).

Lastly, there are several studies conducted under laboratory conditions to understand the impact of microplastics on marine organisms. These include investigating the impact of PS and PE on goldfish [148], the effect of PS on fathead minnow [149], and the effect of PP on marine copepod [150]. Please note that for the laboratory simulated studies, the major ocean sink information has not been included in **Table 2**.

6. Conclusion

The microplastics in the marine environment pose adverse effects on marine organisms, which eventually impact human health. Therefore, for the well-being of humans as well as the conservation of the environment, microplastic pollution is extensively investigated by researchers and scientists around the world. This study summarizes the sources of microplastics (primary and secondary), along with their characterization based on chemical composition, size, and shape. The abiotic and biotic degradation of these microplastics is discussed, showing how various macroplastics (i.e., plastic debris) break down into smaller fragments under the effects of various environmental factors (e.g., temperature, sunlight, and biological agents), chemical damage, and mechanical abrasion. Once formed, the marine habitat serves as the primary sink for the microplastics. The distribution and fate of the microplastics in the marine environment depend on the density, size, shape, and chemical composition of the microplastics, as well as the environmental factors (primarily wind and ocean current velocities). If the density of the microplastic is lower than that of the regional water, the microplastics remain suspended in the gyre (surface waves) and are prone to horizontal distribution because of wind and ocean current velocities. If the density of the microplastic is higher than that of the regional water or its density increases because of biofouling and aggregate formation, it would sink to the bottom of the marine habitat. Once sunk, microplastics can either accumulate in the marine sediment, or they can be redistributed because of bottom water current or bioturbation. Therefore, it is challenging to predict the fate of marine microplastics and requires the attention of researchers to fill the knowledge gap, specifically on the ecotoxicological impact of microplastic on the marine environment. An investigation is needed to study the mechanism of microplastic and chemical pollutant sorption by marine organisms as well as their mode of interaction, evaluate the route of transfer of these contaminants along the food web, and investigate the risk of microplastics on marine organisms as well as human.

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Conflict of interest

The authors declare no conflict of interest.

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