Distribution, Migration and Ecological Effects of Microplastics in Marine Environment

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Abstract. The issue of microplastic pollution has garnered significant attention from governments worldwide and the academic community. Numerous scholarly investigations and regulatory frameworks have been developed pertaining to microplastics. This article presents a comprehensive survey of the advancements made in the investigation and study of microplastics in the global marine ecosystem. It introduces the fundamental characteristics of microplastics, including definitions, classifications, and sources, as well as the patterns of distribution and migration observed in the marine environment. This study also presents the harmful effects of microplastics on marine animals and the resulting ecological impacts on marine systems. Additionally, it discusses worldwide strategies for managing microplastics in marine environments and explores potential avenues for future research in this field. Studies revealed that microplastics are mostly generated and released as a result of human activities. These microplastics tend to gather predominantly on the surface of the North Pacific and North Atlantic regions, which have the highest population density. Once marine species consume microplastics and other harmful pollutants transported by microplastics, these substances have the potential to be transferred down the biological food chain and ultimately enter the human body. Future studies of microplastics should prioritize the rapid characterization and quantification of microplastics in intricate samples, the biological interventions to influence the destiny of microplastics, and the examination of the interplay between microplastics and other contaminants. This article provides a comprehensive overview of the potential outcomes of microplastics and the associated factors and consequences at each stage.

Keywords: Microplastics; microplastic debris; microplastics pollution; marine ecosystem; marine environment.

1. Introduction

The term “microplastics” was initially introduced in the scientific literature by Thompson et al. to denote small plastic particles and fibers [1, 2]. The size of microplastics has been defined differently in different studies, including but not limited to: > 1.6 μm, < 1 mm, < 2 mm, < 5 mm, < 10 mm. The U.S. National Oceanic and Atmospheric Administration (NOAA) now defines the term microplastics as tiny, pervasive plastic particles <5 mm in diameter. The sources of microplastics can be categorized into primary sources and secondary sources. Primary microplastics are plastic microbeads with a particle size less than five millimeters and are produced during the manufacturing process. These microplastics are commonly found in industrial and domestic items, such as cleaning toiletries, cosmetics, and pharmaceuticals. Secondary microplastics are generated as a result of the disintegration of sizable plastic items in both marine and terrestrial environments, facilitated by various physical, chemical, and biological mechanisms. These mechanisms include erosion, wave-induced actions, abrasion, photo-oxidation, temperature fluctuations, corrosion, and biodegradation activities.

Microplastics are frequently detected in marine ecosystems, including coastal areas, saltwater, seafloor sediments, and even Arctic and Antarctic Sea ice [2]. These microplastics are transported by ocean currents and atmospheric winds. The primary pathway via which microplastics enter marine environments is mainly through terrestrial ecosystems. Microplastics widely present in terrestrial ecosystems as a consequence of anthropogenic actions. The ease of migration of microplastics is facilitated by their characteristics, including their lightweight, durability, buoyancy, and shape. These

attributes enable microplastics to be readily transported by ocean currents and wind patterns. Microplastics have higher concentrations in coastal waterways, particularly in regions characterized by high population density, coastal tourism, and extensive industrialization. Existing research indicates that the source of microplastics in the ocean is derived from terrestrial plastic waste. This includes the release of industrial pollutants near marine environments, the discharge of urban domestic waste, and activities related to fishery productivity. The largest sources of microplastics are synthetic fibers derived from industrial laundries and household textile materials. Tire dust particles generated by vehicular activity and urban dust resulting from the degradation of infrastructure constitute two other significant sources of microplastics. In addition, road markings, which include materials such as paint, thermoplastics, and prefabricated polymer tapes, as well as ship coatings, which consist of substances like paint, polyurethane, and epoxy resin all contribute to the sources of microplastics to some extent. The aforementioned microplastics are introduced into the marine environment via many water sources, including wastewater discharges, surface waters, and freshwater systems [2]. The growth in microplastics is also attributed to waste disposal, surface runoff, and atmospheric fallout. Furthermore, the generation of microplastics is also significantly influenced by maritime activity. For instance, the utilization of fishing or recreational fishing equipment such as boxes, nets, and ropes may degrade and subsequently transfer into the marine environment from the intertidal zone. Plastics containing chromophores undergo photochemical reactions upon exposure to ultraviolet (UV) radiation, resulting in the susceptibility of their surface to fragmentation. Consequently, the formation of microplastics is influenced by physical abrasion mechanisms, including wind, waves, and sand.

In recent years, microplastics have attracted global interest and emerged to become a prominent area of research as an emergent pollutant. There is a growing recognition among people of the increasing severity of microplastic pollution and the need for further study in this field. There has been a notable expansion in global research efforts, encompassing not only marine organisms but also organisms inhabiting various aquatic environments, and even extending to human beings. Numerous empirical studies conducted on short-term biological exposure have demonstrated that microplastics permeate the organism via the digestive system and amass within the body, resulting in diverse physiological consequences. These include but are not limited to malnutrition, disturbances in reproductive capacity in terms of both quantity and quality of offspring, the onset of thrombotic events, neurotoxic manifestations, and additional adverse effects. The removal of microplastics from the human body shows significant challenges and carries substantial implications for potential health hazards. Researchers found the presence of microplastics in food samples ingested by individuals.

This article aims to examine the distribution characteristics and migration pathways of microplastics in the marine environment, provide a summary of the toxicological effects of microplastics and their ecological consequences on the marine environment, evaluate the effectiveness of current microplastic governance strategies, and explore potential areas of focus for future microplastic research.

2. Distribution and Migration of Microplastics in Marine Environment

2.1. Distribution of Microplastics

2.1.1 Distribution characteristics of microplastics in virous sea areas

The primary pathway via which land-based plastic garbage infiltrates the ocean is by stormwater runoff into streams or direct discharge into coastal waters. In 2019, approximately 368 million metric tons (MMT) of plastic were produced globally, with the cumulative number of particles approximately 15-51 trillion [3, 4]. 50% of the plastics produced are buoyant [5]. 60-64% of the plastic particles enter the open ocean waters from coastal outlets. Microplastic debris is more susceptible to ocean-level circulation patterns due to its small size. The distribution pattern of microplastics floating on the sea surface is consistent with the predictions of ocean surface circulation

models, indicating that microplastic particles are transported by surface ocean currents and accumulated in five large subtropical circulation convergence zones (Fig. 1), with a total amount of approximately 7,000 to 35,000 tons.

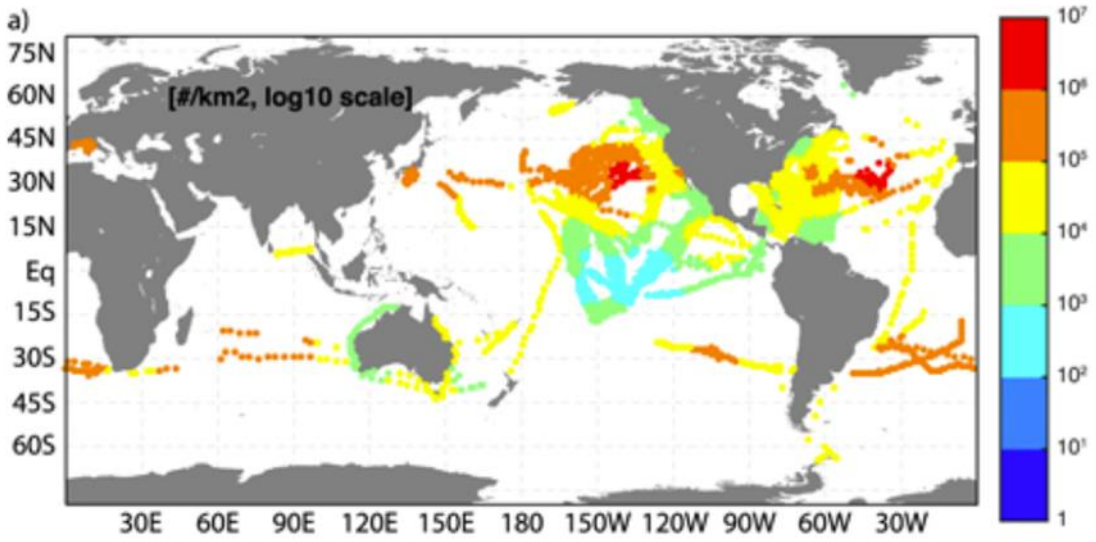


Fig. 1 The global location and standardized microplastic count of all surface trawl data, on a log10 scale [4].

The North Pacific and North Atlantic accumulation zones together cover an area equivalent to the combined continental regions of Australia and the United States. The greatest accumulation zones are located in the subtropical gyre of the Northern Hemisphere [6, 7]. This is explained by the Northern Hemisphere's larger population as well as its more developed economy and industry. Consider the North Pacific's plastic burden, which is the largest and most expansive mass reservoir [4]. The coast of the United States and the Asian continent, which is home to 1/3 of the world's coastal population, are the two regions where substantial quantities of plastic waste are deposited into the ocean [5]. Conversely, in the tropics and the Southern Hemisphere (between 45° south and 45° north latitudes, as well as on the isolated Western Australian coastline), microplastic concentrations are significantly lower. There is less marine waste dumped because of smaller populations and lower industrial activities. The northern and southern hemispheres also have less confluence due to wind and ocean current patterns. The middle of the ocean basin exhibits a discernible demarcation between the accumulation zones in the northern and southern hemispheres, as the transfer of material over the equator is limited to select coastal regions [6].

2.1.2 Concentration and spatial distribution of microplastics in the ocean

The size distribution of microplastic fragments in water mainly follows the abundance-size power law [5]. Plastic objects gradually break into larger amounts and smaller sizes under physical and biological processes, with the number of debris gradually increasing towards smaller sizes. At the same time, the continuous steady input and fragmentation of large plastic objects results in a stable volume size distribution. At the same time, the spatial distribution of microplastics will also be affected by the source of microplastics. The number of microplastics and population density are significantly correlated (Fig. 2), while the average particle size of microplastics is not clearly associated.

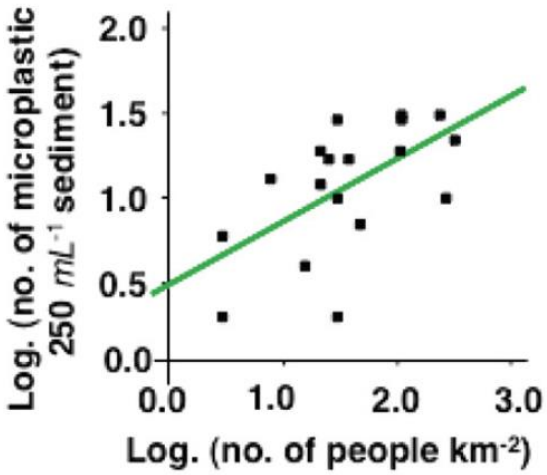


Fig. 2 Relationship between population density and number of microplastic particles in sediment from sandy beaches [9]

2.2. Migration pathways of microplastics in the marine environment

While widespread accumulation of microplastics is found in ocean circulation and shallow water sediments, a significant portion of microplastics enter different sinks. Possible sinks for buoyant plastic debris encompass fragmentation (to undetectable sizes), biofouling (sinking due to loss of buoyancy), shore accumulatio, and marine ingestion (ingested and subsequently reduced small size (e.g., digestive grinding or excretion) [4]. Biofouling is a process where a sticky layer called biofilm is formed by microorganisms, algae, and debris. Microplastics provide a suitable matrix for biofilm formation, leading to their adhesion. Biofilms can also act as sticky surfaces, promoting the adhesion of microplastics. Under maritime conditions, fouling organisms can accumulate and build biofilms quickly, which can lead to a rise in the density of buoyant plastic debris over time [7]. Moreover, a variety of oceanographic phenomena can aid in the movement of microplastics downward. Large volumes of particle-laden water are transferred both vertically and horizontally by these processes, which include saltwater subduction, offshore convection, intense coastal storms, and dense shelf water cascades [8, 9].

3. Interaction Between Microplastics and Marine ecosystems

3.1. Toxicological Effects of Microplastics on Marine Life

The effects of marine debris on marine life are particularly concerning because they can have far-reaching effects and are dangerous if consumed [10]. Ingestion of microplastics causes biological responses through toxicological and chemical mechanisms. Studies have shown adverse effects on the reproduction of oysters exposed to polystyrene microplastics, including reduced sperm motility, altered energy allocation, and reduced larval survival, highlighting the reproductive risks associated with microplastic exposure [11]. Ingestion of microplastics can also cause oxidative stress, inflammation, and cell damage in marine organisms, affecting tissue and intracellular absorption [12]. Research by Mattsson et al. shows that exposure to polystyrene microplastics can lead to impaired swimming behavior and metabolic disorders in fish [13]. It has been demonstrated that small anthropogenic debris can harm bodily tissue, resulting in gastrointestinal tissue cell necrosis, inflammation, and laceration [14]. At the same time, the ingestion of microplastics also has negative behavioral effects on marine life, mainly including predation and survival of young fish. Microplastics have been shown to alter the foraging behavior and prey selection of gobies, reducing the fish's predatory performance and efficiency [15]. Exposure to microplastics increases mortality by reducing the ability of juvenile fish to detect predators and find shelter [16]. Coppock et al. showed that ingestion of microplastics disrupts the feeding behavior and energy assimilation of copepods,

potentially affecting their survival and reproductive success [17]. In addition, microplastics are incapable of traversing the digestive tract and can cause intestinal obstruction. The accumulation of non-nutrient elements may lead to malnutrition, false satiety, ultimate hunger, and reduced physical capability. This could lead to a significant decline in the world's fish stocks. Also, the buoyancy of plastic may make it more difficult for midwater fish to return to deeper water [18]. The above toxicological effects of microplastics on marine organisms are summarized in Table 1.

Table 1. Toxicological effects of microplastics on marine species [11-18].

Species Name	Toxicity	Reference
Oysters	Reduced sperm motility, altered energy allocation, and reduced larval survival	[11]
Blue Mussel Mytilus Edulis L.	Causing oxidative stress, inflammation, and cell damage, affecting tissue and intracellular absorption	[12]
Fish	Leading to impaired swimming behavior and metabolic disorders	[13]
Pelagic and demersal fish	Causing physical damage, cell necrosis, inflammation, and lacerations of gastrointestinal tissue	[14]
Gobies	Altering the foraging behavior and prey selection of gobies, reducing the fish's predatory performance and efficiency	[15]
Juvenile fish	Reducing the ability to detect predators and find shelter	[16]
Copepods	Disrupting the feeding behavior and energy assimilation, affecting their survival and reproductive success	[17]
Midwater fish	Making it difficult to return to deeper water	[18]
Worldwide fish populations	Causing intestinal obstruction, leading to malnutrition, false satiety, ultimate hunger, and reduced physical capability.	[18]

3.2. Ecological Effects of Microplastics on Marine Ecosystems

3.2.1 Distribution characteristics of microplastics in different sea areas

A diverse range of marine organisms, including fish, crabs, seagulls, and plankton, have been observed to ingest microplastics [10]. Tiny plankton species can consume plastic fibers because they can be as small as 1μm in diameter and 15μm in length in the environment [19]. Desforges et al. demonstrated that two zooplankton species—New Calamus copepods and Copepoda—that are essential to the North Pacific marine food web consume microplastic in the open ocean [20]. Organisms occupying lower trophic levels within marine ecosystems exhibit a heightened susceptibility to erroneously seeing plastic materials as viable sources of sustenance. Murray and Cowie initially shown in 2011 that feeding fish sown with polypropylene fibers to lobsters could transfer microplastics from prey to predators [10]. Approximately 35% of the planktonic pelagic fish examined in the North Pacific Central Gyre had microplastics in their stomachs, according to fish dissections. The average amount of plastic consumed by fish rose quantitatively as their size increased. 83% of Nephrops sp. in the Sea of Clyde, Scotland, had consumed plastic. This economically significant omnivorous benthic crustacean mostly consumes pieces of plastic bags and monofilament. Plastic debris was first discovered in the intestinal tracts of seabirds in the 1960s [19]. A Dutch study team discovered in 1982 that an average of 34 plastic bits were carried by each fulmar, accounting for 94% of the samples of fulmars that contained plastic. Tanaka et al.'s study looked into the build-up of chemicals derived from plastic in the tissues of seabirds that had eaten marine plastic; it identified possible chemical transfer from microplastics to biological tissue at higher trophic levels, which could have an impact on the birds' general well-being and ability to survive [21]. In addition, through looking at anthropogenic waste found in fish and shellfish that are bought straight out of the seafood markets, human health may be impacted if marine animals consume human waste since it may cascade up in the food chain. The discovery of microplastics in over 25% of the assessed individual animals and over 50% of the fish that fishermen and fish traders sell for human

consumption raises the possibility that human garbage has permeated the marine food web through seafood [14]. Under certain circumstances, microplastic particles from marine animals may pose a serious threat to the safety and quality of local food in places where seafood is the predominant source of protein for the indigenous population, particularly in Indonesian island villages.

3.2.2 Microplastics can serve as carriers of other pollutants and invasive species.

Microplastics have a large surface area to volume ratio and therefore can facilitate the transport of contaminants [10]. Microplastic particles contribute significantly to the transfer of toxic substances to living organisms. This applies both to certain substances that are incorporated into the plastic during the manufacturing process, such as monomers, oligomers, plasticizers, flame retardants, and antimicrobials, as well as to substances that are later adsorbed onto the microplastics similar to other toxic and persistent bioaccumulators. Contaminants from plastics have the ability to enter living organisms once they are consumed. Once ingested, contaminants have the potential to be transferred from plastics to living organisms. Similarly, consuming fish and shellfish can expose people to toxins found in anthropogenic waste [14]. Furthermore, plastic debris may significantly increase the colonization of fauna in subtropical and high-latitude regions in cases where species are invasive. While unlikely to become a major transport route, drifting on marine debris may provide additional methods for the spread of invasive species.

4. Microplastics Governance Strategies and Prospects

4.1. Current Global Microplastics Governance Policies and Measures

In general, international policies and initiatives to control microplastics seek to lessen their discharge into the environment and enhance waste management techniques in order to recognize and lessen the negative effects that microplastics have on the environment and human health. To encourage the appropriate disposal of plastic garbage, numerous nations have implemented waste management techniques, recycling initiatives, and reductions in plastic sources [22]. Microbead-Free Waters Act, enacted by the US, UK, Canada, Austria, Belgium, Norway, and other countries, forbids the deliberate manufacture and distribution of non-biodegradable plastic microbeads in rinse products intended for personal hygiene use. In 2017, the United Nations Environment Program (UNEP) urged all UN member states to make policies and actions aimed at preventing microplastics from getting into the maritime environment top priority. Many European countries have passed Extended Producer Responsibility (EPR) legislation, making the industry responsible for the entire life cycle of the products they produce to reduce plastic use and increase plastic reuse and recycling [23].

Governments have also launched campaigns to educate the public about the impacts of microplastics and promote behavioral change, for example by raising awareness of microplastics and providing incentives for individuals to combat the issue. The Australian and US governments have effectively reduced beverage container waste through container deposit legislation (CDL), or small cash incentives for containers as low as 5-10 cents [23]. In addition, the government should encourage citizens to participate in cleaning beaches scientifically to raise awareness [24]. A lot of countries have made investments in water treatment technologies designed to filter out microplastics from wastewater prior to its release into aquatic environments. Membrane bioreactors are widely used in wastewater treatment facilities in Canada to disperse only water and tiny particles following primary and secondary treatment using crossflow filtration [22]. The EU's TA/2019/0071 announcement in 2019 limits the content of microplastics in treated wastewater and sewage sludge to address the performance issues of microplastics in sewage treatment plants. The mentioned microplastics governance strategies are summarized in Table 2.

Table 2. Overview of Global Microplastics Governance Strategies [22-23].

Country	Purpose	Strategy	Reference
United States, etc.	To reduce primary sources of microplastics	Prohibiting the intentional production and sale of rinse products with non-biodegradable plastic microbeads	[22]
United Nations	To prevent microplastics from entering the marine environment	Prioritizing relevant policies and measures	[22]
European Countries	To reduce plastic use and increase plastic reuse and recycling	Passing the Extended Producer Responsibility (EPR) legislation, making the industry responsible for the entire life cycle of their products	[23]
Australia, United States	To reduce beverage container waste	Passing container deposit legislation (CDL), rewarding small cash incentives for containers	[23]
Canada	To filter wastewater to eliminate microplastics before releasing it into water bodies	Investing in water treatment technology	[22]
European Union	To solve the problems with microplastics' performance in sewage treatment facilities	limiting the content of microplastics in treated wastewater and sewage sludge	[22]

4.2. Direction of Future Research on Microplastic Management

In order to establish suitable remediation strategies to address the issues related to plastic pollution, scientists and environmentalists must properly sample, identify, and quantify microplastics in the environment. It is challenging to gather enough microplastic particles for chemical analysis from complex samples like food. Due to the low detection frequency and high detection limit of small microplastics, researchers must design effective methods to perform chemical analysis of these particles within seconds [3]. In addition, establishing quantitative analysis technology and unified quantitative units for microplastics in different environmental media is also a new research trend. The use of biological means to intervene in the fate of microplastics has also been widely mentioned, such as reducing the number of chemicals used in plastic manufacturing by adding biological products, using plant-derived monomers and plant-based polymers to make plastics [24]. Microorganisms existing in the environment that can decompose microplastics should be further explored and combined with existing removal technologies [22], and the use of microbial enzymes should be attempted to lower the environmental harm caused by microplastics [3]. The interaction between microplastics and other pollutants it carries is also an important topic in ecotoxicity research. In addition to heavy metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons and antibiotics, the mechanism of the impact of microplastics on the migration behavior of other pollutants is not yet clear. Theoretical research on the toxic effects of microplastics, heavy metals, and organic pollutants in composite systems still needs to be strengthened. How chemical pollutants leached from microplastics are adsorbed into the tissues of aquatic organisms, the interaction between microplastics and persistent organic pollutants [24], and the impact of water properties such as pH value and ionic strength on the ability of microplastics to adsorb pollutants are all potential research topics.

5. Conclusion

Microplastic contamination is prevalent on a global scale. Current scientific research focuses mainly on the forms and origins of these tiny pollutants, as well as their associated health risks. The primary topic of this article centers on the research of microplastics throughout the marine ecosystem. This paper introduces the definition and categorization of microplastics, plus an overview of the origins of microplastics in the ocean. The distribution of microplastics after their entry to the marine ecosystem is influenced by both ocean surface circulation patterns and anthropogenic causes. This article emphasizes the toxicological effects after the ingestion of microplastic particles by marine creatures, as well as the resulting impacts that occur upon their incorporation into the biological food chain. This article summarizes of the current global efforts to reduce microplastic pollution. For the future stage, the academic community should vigorously expand scientific methods for rapid, effective quantification and characterization of microplastics in complex samples and complex environments, explore the use of environmentally friendly biological means to produce and degrade plastics and pay more attention to the interrelationship between the environment and pollutants carried by microplastics. In addition, it is imperative for citizens to proactively engage with the government's education and policy initiatives. It is crucial to remain vigilant regarding the proliferation of microplastics inside ecosystems and take measures to eradicate the utilization of plastic microbeads in everyday activities. Furthermore, adopting scientific methodologies for recycling and reutilizing plastic products is of utmost importance.

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