Research Progress on the Migration Pathways and Ecological Effects of Microplastics in Marine Food Webs

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Abstract. Marine microplastic (MPs) pollution poses a significant threat to marine ecosystems and human health. Understanding its migration patterns and ecological impacts within the food web is crucial for marine environmental protection. This paper reviews the process of MPs migration through different trophic levels in marine food webs, analyzes the mechanisms influencing their transfer efficiency, and assesses the ecological risks from individual to ecosystem levels. We find that MPs are transferred from primary producers through primary consumers, omnivorous animals, and eventually to carnivorous animals. Meanwhile, multiple factors, including the intrinsic properties of MPs, biological factors, and environmental media, interact to influence their transfer within the food web. Furthermore, MPs can harm individual organisms and populations. This paper systematically summarizes the key driving mechanisms of MPs transfer in marine food webs and provides valuable insights for effectively managing plastic pollution and ensuring the health and sustainable development of marine ecosystems.

Keywords: Microplastics (MPs); Marine food web; Trophic transfer; Ecological hazards.

1. Introduction

Microplastics (MPs) are defined as plastic particles with a diameter of less than 5 mm. To distinguish them from nanoplastics (ranging from 1–999 nm), solid synthetic organic polymer particles with diameters between 1 μm and 5 mm are generally classified as microplastics[1]. Recent statistics indicate that approximately 24.4 trillion MPs exist in the oceans worldwide, with an annual input exceeding 8×10^6 t[2], posing significant threats to marine ecosystems. On one hand, marine organisms ingest MPs can lead to organ blockages, developmental abnormalities, and immune system impairments. On the other hand, MPs may transfer through the food chain to higher trophic levels, ultimately entering the human body and posing potential health risks.

Early studies on marine organisms ingest MPs primarily focused on the presence and characteristics of MPs in the gastrointestinal tracts of marine biota from specific marine regions. For instance, Avio et al.[3] characterized the abundance of MPs in 500 biological samples (including fish and invertebrates) from the Adriatic Sea, revealing the widespread ingestion of MPs among marine organisms. However, this study did not address whether MP ingestion was influenced by trophic interactions. Cedervall[4]was the first to report the trophic transfer of polystyrene particles (PS), yet this study did not investigate the factors influencing MP ingestion across different marine species within the food web. Trophic transfer is a critical pathway through which MPs reach higher trophic-level organisms, and the feeding strategies of different trophic groups play a decisive role in determining the efficiency of MP transfer.

This review examines the trophic transfer of MPs in complex marine food webs, and analyze key factors influencing MP transfer efficiency. The ecological risks of MPs are comprehensively assessed, ranging from impacts at the individual level to those at the ecosystem level.

2. Pathways and Characteristics of Microplastic Transport in Marine Food Webs

MPs in marine environments primarily originate from anthropogenic activities and are transported under the influence of various environmental factors, including wind, precipitation, and riverine input. These processes collectively contribute to the eventual accumulation of MPs in marine ecosystems[5]. Based on their sources, MPs can be classified into two major categories: land-based and marine-based inputs, with the former being the predominant contributor. Land-based MPs primarily derive from plastic waste generated through industrial and domestic activities, which enter aquatic systems via wastewater discharge, surface runoff, and atmospheric deposition, and ultimately flow into the ocean. Marine-based MPs, by contrast, are mainly produced through the abrasion of ships and aquaculture equipment.

MPs in marine environment poses a potential and serious threat to marine ecosystems and human health. And MPs transport and distribution in ocean are significantly influenced by their intrinsic physical properties, particularly density, and external hydrodynamic conditions.

Lower densities MPs tend to remain buoyant and float at or near the ocean surface. Their horizontal movement is largely driven by ocean currents, which facilitate either homogeneous or heterogeneous dispersion across different water columns. Conversely, higher densities MPs are more likely to exhibit vertical transport dynamics. Under the influence of wave action, MPs may settle to the seafloor, while others can be resuspended or transported into deeper water layers, resulting in their eventual deposition in the benthic environment[6].

2.1 Pathways of Microplastics Entry into Marine Food Webs

2.1.1 Primary Producers

Planktonic organisms, particularly phytoplankton, are the initial trophic level through which MPs enter marine food webs. Their feeding behavior and physiological responses jointly influence the efficiency of MP transfer. As primary producers, phytoplankton cannot active ingestion and rely primarily on photosynthesis for growth. However, MPs tend to aggregate and adsorb in phytoplankton-rich zones, such as the ocean surface mixed layer, leading to the formation of "MP-phytoplankton aggregates." These aggregates can then be introduced into the food web via grazing by higher trophic organisms. Furthermore, Li et al.[7]reported that smaller-sized nanoplastics are capable of penetrating cellular membranes and entering phytoplankton cells directly, thereby facilitating the upward transfer of MPs through trophic interactions.

2.1.2 Consumers

MPs can also enter marine food webs by direct ingestion or respiratory intake by various consumers. These pathways include filter-feeding, predation, and passive ingestion from surrounding waters. Recent studies have detected the presence of MPs in fish and zooplankton worldwide, including the South China Sea[8], the Ionian Sea of Greece[9], and the Arctic Ocean[10]. Notably, fish from the South China Sea exhibited relatively high levels of MP contamination, with an average abundance of approximately 1.96 particles per individual.

2.2 Migration of Microplastics within Marine Food Webs

2.2.1 Transfer of Microplastics to Primary Consumers

Zooplankton are the primary consumers in marine ecosystems and feed predominantly on phytoplankton and microorganisms. During predation, zooplankton may ingest phytoplankton that are associated with MPs, or directly mistake MPs for food particles. Cole et al.[11] demonstrated that zooplankton not only ingest MPs through consumption of phytoplankton but are also capable of ingesting PS even in the absence of natural prey. Following ingestion, zooplankton themselves are preyed upon by organisms at higher trophic levels, thereby facilitating the upward transfer of MPs along the food web.

Outi et al.[12] found that the trophic transfer potential of MPs from mesozooplankton to macrozooplankton, indicating that MPs can effectively move between trophic levels via biological interactions. Similarly, Li et al.[13]found that among five zooplankton taxa sampled from the northern South China Sea, MPs found in their bodies were of comparable sizes. Moreover, individuals occupying higher trophic positions tended to contain greater quantities of MPs per organism, suggesting a clear trend of trophic-level dependent bioaccumulation of MPs within the planktonic food web of this region.

Due to their small size and variable densities, MPs can exist in diverse environmental compartments including sediment layers, the water column, and even within zooplankton assemblages of similar size ranges. This enables MPs to be mistakenly ingested by a variety of predators with different feeding strategies, particularly filter-feeding marine fish[11][14][15].

2.2.2 Transfer of Microplastics to Omnivorous Marine Organisms

Omnivorous marine organisms, (such as crabs , anchovies, knife anchovies, etc.) consume both plant-derived organic matter (such as detritus, phytoplankton, algae) and small animal prey (such as small arthropods, mollusks). These organisms generally occupy higher trophic positions than plankton within the marine food web.

The transfer pathways of MPs along omnivorous species groups are diverse and complex. Paul et al.[15] demonstrated MPs can be transferred along the food chain from mussels (Mytilus edulis) to crabs (Carcinus maenas). Cedervall et al. [4] further investigated transport of nanoplastics along a marine food chain and discovered that nanoplastics can migrate along the food chain from Scenedesmus obliquus to Daphnia magna to crucian carp, affecting the lipid metabolism and behavioral activities of the fish.In another study, Tanaka et al.[16] discovered that out of 64 Japanese anchovies (Engraulis japonicus), 49 had MPs in their bodies, mostly polyethylene (PE) or polypropylene (PP), which highly coincided with the plastic fragments in the surface seawater where they lived, indicating that omnivorous organisms may ingest MPs while preying on plankton.

2.2.3 Transfer of Microplastics to Carnivorous Marine Organisms

Carnivorous marine organisms, including many high-trophic-level fish species (such as tuna, sharks, cod), cephalopods (such as squids, cuttlefish), and predatory crustaceans (such as mantis shrimp), primarily feed on other animals within the marine food web. Carnivorous organisms ingest MPs by preying on smaller fish or invertebrates contaminated with MPs.

Initially, Cecilia et al.[17]discovered that MPs can enter seals through a species of lanternfish (Electrona subaspera) by analyzing the feces of fur seals (Arctocephalus spp.), suggesting that MPs can be transferred between prey and higher-order predators. Lusher et al.[18] reported that the abundance of MPs in the stomachs of certain carnivorous fish was comparable to that in their planktonic and small fish prey, reinforcing the notion of trophic transfer along the food chain.

Moreover, Gao et al.[19] found that *C. lucidus* has a broader habitat range and more diverse feeding behavior than *L. polyactis*. Therefore *C. lucidus* was likely to encounter higher levels of MPs throughout its life cycle, including that environmental factors, particularly habitat characteristics, can significantly influence the degree of MP exposure and accumulation in carnivorous marine species.

3. Key Factors Influencing the Trophic Transfer of Microplastics in Marine Food Webs

3.1 Intrinsic Properties of Microplastics

3.1.1 Particle Size and Morphology

MPs size is one of the most critical factors determining their potential for biological ingestion[20]. Planktivorous organisms tend to ingest particles in the size range of 1–20 μm, which overlaps with the dimensions of many planktonic species. For instance, the copepod Centropages typicus exhibited a significantly higher ingestion rate for 7.3 μm MPs compared to 30.6 μm particles[9]. Furthermore, bivalves such as the blue mussel (Mytilus edulis) and oysters demonstrate clear selectivity in their ingestion of MPs, preferring smaller spherical particles (such as 19 and 113 μm) while exhibiting rejection behavior towards larger particles (287, 510 and 1000 μm) and fiber-shaped MPs. Notably, the ingestion rate of 19 μm MPs was significantly higher than that of 1000 μm particles[21][22][23].

3.1.2 Density of Microplastics

MPs density is a main factor determining their vertical distribution in the marine environment, which in turn influences the likelihood of ingestion by marine organisms[24]. High-density plastics, such as polyvinyl chloride (PVC) and polyethylene terephthalate (PET), tend to sink to the seafloor, thereby increasing the exposure risk for benthic organisms[25]. Nikhil et al.[26] found that benthic fauna along the west coast of India ingest PET and PVC from sediments, with the highest MP abundance observed in the gastropod P. biangulosa and the lowest in the bivalve A. hankeyana. Furthermore, PET was absent in T. quadrapicalis, and PVC was detected only in J. philippinarum, suggesting that MP ingestion exhibits a high degree of species-specific selectivity.

Additionally, Khalida et al.[27] detected MPs in all 21 fish species collected from the Yangtze River estuary. And the ingestion rates followed the trend: demersal > benthic > benthopelagic ≈ pelagic. In contrast, low-density plastics, such as PE, PS, PP, tend to remain suspended in the water column for extended periods, posing greater risks to epipelagic and mesopelagic organisms[28][29]. Zhang et al.[30] confirmed the presence of spherical MPs in upper-middle layer fish, with significant differences in ingestion levels between *Konosirus punctatus* and *Alepes djedaba*, the former exhibiting a notably higher MP ingestion rate.

Over time, MPs undergo degradation due to biological, physical, and chemical processes, which can alter their shape, size, and density, leading to redistribution within the water column[31]. For example, Rummel et al.[32] found that benthic fish exhibited a lower average MP intake compared to pelagic fish, further supporting the notion that MP contamination varies by species and habitat. Therefore, MP pollution assessments must consider regional environmental contexts and species-specific ecological niches.

3.2 Biological Factors

3.2.1 Feeding Habits of Organisms

Due to differences in diet, MPs ingestion varies significantly among fish species. In early studies, Ricardo et al.[33] found that omnivorous fish ingested more fibrous MPs compared to herbivorous and carnivorous species. However, subsequent research has revealed different trends: Lenin et al. [34] observed that carnivorous species exhibited the highest ingestion rates of MPs, followed by planktivorous species, with omnivorous species showing the lowest rates. Furthermore, Lenin et al.[34] also noted that marine organisms with low feeding selectivity are more likely to ingest larger-sized MPs. This finding further underscores the importance of feeding behavior and selectivity in determining an organism's exposure risk to microplastics.

3.2.2 Physiological Characteristics

Organisms significantly influences their exposure risk to MPs.Larger individuals generally exhibit higher food intake rates and broader foraging ranges, which increases the likelihood of exposure to prey and environments contaminated with MPs [35]. Additionally, larger predators are often indirectly exposed to MPs through the consumption of contaminated prey.

In contrast, smaller organisms (such as zooplankton) are more prone to ingest MPs with small particle sizes (micron or submicron scale) due to the comparable size between their feeding structures and the plastic particles, and smaller organisms have weak selectivity during filter feeding or swallowing, which leads to a high probability of accidental ingestion.

Moreover, for the same species, larger individuals may accumulate more MPs due to their greater gut capacity and longer retention times. Longer gut provides a longer residence time for MPs, increasing the contact between MPs and digestive fluids or intestinal epithelium, thereby enhancing the potential for micro- or nano-sized MPs to penetrate the gut barrier and enter bodily tissues or fluids (such as blood or lymph). This process intensifies the absorption and bioaccumulation of MPs within the organism. In contrast, smaller organisms with shorter guts tend to have faster gastrointestinal transit rates, allowing MPs to be expelled more readily with feces, thus reducing the risk of internal accumulation[36].

3.3 Environmental Media

3.3.1 Physicochemical Properties of Seawater

Temperature directly influences the physical aging and degradation rate of MPs. Higher seawater temperatures can accelerate the surface cracking of polymers, leading to the release of smaller plastic particles that are more readily ingested by benthic organisms. Additionally, temperature affects the metabolic rate of marine organisms, indirectly influencing their feeding and excretion rates, thereby altering the retention time and transport pathways of MPs within their bodies.

Salinity affects the suspension and sedimentation behavior of MPs in water. Under high salinity conditions, MPs swelling and density can change, influencing their vertical distribution and the likelihood of ingestion by organisms from different functional groups.

pH can regulate the surface charge of MPs and their adsorption capacity for organic substances and metal ions. MPs that have adsorbed pollutants under pH regulation may be ingested by organisms because their altered appearance mimics the chemical signals of natural organic matter. Alternatively, they may be rejected due to electrostatic repulsion generated by surface charge.

3.3.2 Hydrodynamic Conditions

Ocean currents, tides, and wave action are key hydrodynamic forces that significantly enhance the horizontal and vertical mixing of MPs in the marine environment. These processes increase the likelihood of interactions between MPs and marine organisms of various trophic levels and habitat zones. For instance, in dynamic environments such as coastal and estuarine regions, the frequent resuspension and periodic deposition of MPs are prominent. This leads to a higher probability of repeated ingestion by benthic organisms or sediment-ingesting species in these areas.

4. Ecological Hazards of Microplastic Transfer Through the Food Web

4.1 Effects on Individual Organisms

Exposure to MPs has varying effects on different species, generally manifested as growth retardation, reduced reproductive capacity, and shortened lifespan[37].

Once ingested, MPs occupy space in the gastrointestinal tract, inducing a false sense of satiety that leads to reduced intake of natural food, thereby impairing energy acquisition and growth. For example, certain crustaceans and juvenile fish exhibit decreased growth rates and vitality following MP ingestion. Cole et al.[38] reported that after ingesting MPs, intestinal blockage rate of zooplankton (such as copepods) reached 15–30%, resulting in a decrease in feeding efficiency by more than 40%. Camille et al.[39] found that after multiple exposures to MPs, mussels experience increased energy consumption, reduced growth rates, and downregulated the expression of immune-related genes. Welden et al.[40] investigated the toxicological effects of long-term exposure of Nephropsnorvegicus to high concentrations of polyethylene fibers. The results show that exposure to high concentrations of MPs may reduce their utilization rate of nutrients. Additionally, MPs with sharp edges or rough surfaces may physically damage the digestive tract lining, leading to inflammation, tissue necrosis, or morphological alterations of intestinal structures.

4.2 Effects on Biological Populations

Long-term exposure to MPs not only compromises the health of individual marine organisms but may also pose significant threats to the stability of populations through various pathways. Accumulation of MPs within the digestive tract can markedly reduce feeding efficiency, as observed in species such as the *Nephropsnorvegicus*, leading to diminished nutrient utilization and constrained growth, ultimately reducing population survival rates. Energy metabolism disorders induced by MP exposure may also propagate through the food chain, threatening the viability of organisms at higher trophic levels.

MPs exposure has been shown to directly impair reproductive function in marine organisms. Multiple studies have confirmed reproductive toxicity, including reduced fertilization and hatching rates, as well as abnormal embryonic development. For instance, Oona et al.[41] demonstrated that 90 μm PS inhibited hatching in European sea bass (Dicentrarchus labrax), slowed larval growth, and altered feeding preferences and innate behaviors in the early life stages. Similarly, Sussarellu et al.[42] reported that exposure to MPs at concentrations as low as 23 μg/L significantly decreased oocyte production and sperm motility in Pacific oysters (Crassostrea gigas), while also reducing larval survival rates and developmental progression.

5. Conclusion

This study presents a systematic review of the migration pathways, influencing mechanisms, and ecological impacts of MPs within marine food webs. MPs mainly originate from human activities and enter marine ecosystems through pathways such as terrestrial inputs and marine ingestion. Their transport and spatial distribution are regulated by the combined influence of their intrinsic physical properties (such as density) and external hydrodynamic conditions. In the marine food web, MPs are initially adsorbed by primary producers such as phytoplankton and are subsequently transferred through the trophic chain to consumers with varying feeding strategies (such as zooplankton, fish), following the transfer pathway of "phytoplankton-primary consumers-omnivores-carnivores".

The efficiency of MP transfer through the food web is influenced by the interaction of multiple factors: physicochemical characteristics of MPs (such as particle size, shape, density) determine their bioavailability; biological traits (such as feeding habits, physiological and metabolic features) influence ingestion and retention efficiency; and environmental media (such as seawater temperature, salinity, pH, and hydrodynamic conditions) modulate their transport and transformation behavior. For individual, MPs exposure can induce toxic, such as impaired growth and reduced reproductive capacity. At the population level, chronic exposure may threaten population stability and dynamics. Overall, this study enhances the understanding of the trophic transfer mechanisms of MPs in marine food webs and provides crucial scientific insights to inform strategies for marine plastic pollution mitigation and the preservation of ecosystem health.

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