Research progress on the effects of microplastics on coral reef ecosystems

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Abstract. Marine microplastics, as an emerging pollutant, have attracted increasing attention globally. Coral reefs, the most biodiverse and representative ecosystems in tropical marine regions, play a vital role in maintaining marine ecological balance, supporting fishery resource regeneration, promoting ecotourism, facilitating marine drug development, and providing coastal protection. Characterized by their small size, high abundance, broad distribution, capacity to carry toxic substances, and ease of ingestion and transfer by marine organisms, microplastics have become a significant factor affecting the health of coral reef ecosystems. This review synthesizes the current global distribution of coral reefs, the status of microplastic pollution in coral reef waters, and the impacts of microplastics on corals and other organisms within these ecosystems. It also highlights existing challenges and future research directions, providing important scientific references for managing marine microplastic pollution and protecting coral reef ecosystems.

Keywords: microplastics; coral reefs; ecosystems; pollution; conservation;

1. Introduction

Plastic, a novel material born in the era of the 19th-century Industrial Revolution, is the general term for synthetic polymer materials. With its advantages of being lightweight, waterproof, highly moldable, durable, inexpensive, and colorful, plastic has been widely applied in industry, agriculture, and daily human life. In 2016, the global annual production of plastic exceeded 355 million tons, while the annual consumption of plastic was no less than 240 million tons. However, the recycling rate of plastic is less than 10%[1], which means that a large number of plastic products enter the environment after use. Given that plastics are highly resistant to degradation in the environment, this has led to severe pollution problems. Oceans, being the lowest-lying areas on Earth, have become the ultimate sink for global plastic waste. It is estimated that 8 to 12 million tons of plastic waste enter the oceans annually via various pathways, accounting for 70% to 90% of marine debris[2]. In recent decades, marine plastic pollution has been escalating. Within the marine environment, large plastic debris is broken down into smaller particles through processes such as solar radiation, weathering, thermal oxidation, hydrolysis, and biodegradation. When the particle size is less than 5 mm, these fragments are classified as microplastics[3].

In recent years, microplastics have emerged as novel pollutants that may pose significant threats to the environment[4]. The annual production of plastics continues to rise, driven by their widespread use in diverse fields[5]. When subjected to physical, biological, and chemical processes in the natural environment, plastic waste experiences photodegradation, embrittlement, decomposition, and fragmentation, ultimately resulting in the formation of microplastics[6].

Extended exposure to sunlight can induce photodegradation in plastics, with ultraviolet (UV) radiation triggering oxidation of polymer matrices. This process can cause the rupture of chemical bonds and the subsequent release of additives from micro- and nano-plastics[7]. As an emerging environmental concern, microplastics are pervasive in global aquatic systems. They are found in diverse locations, including coastal intertidal zones, open ocean waters, sea surface layers, deep-sea sediments, equatorial to polar regions, and freshwater rivers and lakes[8]. These microplastics can accumulate within organisms, leading to physical harm such as organ abrasion and intestinal blockages[9]. Additionally, the leaching of monomers and additives from microplastics can induce carcinogenic effects and endocrine disruption in organisms, with the potential to propagate through the food chain and pose threats to marine life and entire ecosystems[10]. Emerging research has increasingly emphasized the potential impacts of microplastic pollution on coral reef ecosystem health[11]. Coral reefs, as the most prominent and typical ecosystems in tropical marine regions, play a vital role in maintaining marine ecological balance, supporting fishery resource regeneration, promoting ecotourism, facilitating marine drug development, and providing coastal protection. However, in recent years, coral reef ecosystems have faced significant threats from both global climate change and human activities[12].

As marine microplastic pollution continues to worsen, research both domestically and internationally has increasingly concentrated on microplastic contamination in coral reef regions. These investigations have clarified the pollution levels, bioaccumulation characteristics, and ecotoxicological impacts of microplastics within coral reef ecosystems. Such findings provide essential data for evaluating the health of coral reef ecosystems and offer novel perspectives for their conservation efforts. This review synthesizes the current research advancements on microplastic pollution in coral reef ecosystems from both domestic and international studies, identifies the current scientific and technological frontiers and key challenges, and suggests future research directions and priorities.

2. Coral Reef Ecosystems

The coral reef ecosystem, comprising corals, fish, benthic organisms, algae, and microorganisms, ranks among the most productive marine ecosystems, comparable to seagrass beds and mangrove ecosystems[13]. It supplies vital nutrients such as nitrogen, phosphorus, and inorganic carbon to the broader marine environment. Characterized by high productivity, species diversity, and rapid material cycling, the ecosystem surrounding reef-building corals supports a vast array of other species by providing critical habitat and resources[14]. Moreover, coral reefs serve as repositories of substantial environmental information and play significant roles in carbon cycling, speciation, and pharmaceutical development[15].

The core of the coral reef ecosystem is the coral itself. Corals belong to the phylum Cnidaria, class Anthozoa, and are marine invertebrates[16]. Coral polyps, which are the individual organisms that make up corals, have a hollow, cylindrical body with an internal gastrovascular cavity[17]. The lower end of the polyp attaches to the reef substrate, while the upper end has a mouth surrounded by tentacles[18]. These tentacles contain specialized cnidocytes, which release nematocysts to paralyze prey when the polyp is threatened or feeding. Corals reproduce both sexually and asexually.

Within coral organisms, a complex mutualistic symbiosis exists between the coral polyps and zooxanthellae (symbiotic algae). On one hand, zooxanthellae reside within the vacuoles of coral endodermal cells, providing over 95% of their photosynthetic products (such as amino acids, sugars, carbohydrates, and small peptides) to the coral to meet its energy demands for movement, metabolism, and reproduction[19]. On the other hand, zooxanthellae obtain essential plant nutrients (such as ammonia and phosphates) from the coral's metabolic waste, which supports their photosynthetic activities[20]. Additionally, a stable symbiotic relationship exists between corals and their associated microorganisms[21], which plays a crucial role in coral health and survival[22]. These microorganisms, including algae, bacteria, archaea, and viruses, are sensitive to environmental disturbances and can influence the physiological state of the coral host[23]. Sun et al.[24] demonstrated that coral bleaching is closely related to the associated microorganisms. Currently, research on coral-associated microorganisms predominantly focuses on microbial diversity and community structure. However, information regarding their functional roles and underlying mechanisms remains limited. The behavior and mechanisms of microorganisms causing coral bleaching remain unclear. The balance between coral symbiotic algae and bacteria is crucial for maintaining the integrity of the coral-algae and coral-bacteria symbiotic systems[25].

3. Status of coral reef distribution

Corals include soft corals and reef-building corals. Coral reefs are mainly formed by the long-term accumulation of calcium secreted by reef-building coral polyps for generations, and coral reefs provide a high-quality living, habitat and breeding environment for marine life[26]. According to research by Smith[27], the global distribution of coral reefs is primarily concentrated in the tropical oceans between the Tropic of Cancer and the Tropic of Capricorn. This distribution is largely influenced by natural environmental conditions, including water temperature, water depth, light availability, salinity, wave action, and ocean currents, as well as by human disturbances. Coral reefs are predominantly found along the continental and island coasts and in the oceanic regions surrounding the equator in the Indian Ocean, the Pacific Ocean, and the Atlantic Ocean (Table 1). Coral reef health is expressed in terms of live coral coverage. Coral reefs have been rapidly degraded in recent decades due to global change, with live coral cover declining by 53% in the Western Atlantic, 50% on the Great Barrier Reef, and 40% in the Indo-Pacific [28]. Among the current status of coral reef degradation in various regions, the Australian region has the mildest performance and the Southeast Asia region has the most serious problem. Studies have shown that only 40% of the world's coral reefs will remain after 2030 [29], and the most common cause of coral reef decline is warming and acidification of seawaters[30]. According to the projections, coral reefs will disappear by the end of the 21st century if the global trend is not effectively controlled[31].

Table 1 Distribution of coral reefs in the world

	Coral reef distribution area	Proportion of coral reef area(%)
Pacific Ocean	Indonesia	30
	Philippines	
	Northern Australia	
	Coast of the Asian continent	
	Other seas in the Pacific Ocean	25
Indian Ocean	Red Sea	30
	Persian Gulf	
Atlantic	Caribbean	14
	North Atlantic	
	South Atlantic	1

4. Microplastics

Since the large-scale production of plastics commenced in the 1940s, their exceptional physical and chemical properties have driven extensive applications across various sectors. As a result, global plastic production and consumption have surged dramatically, reaching nearly 300 million tons by 2013[32]. Plastic waste that is not properly managed during production and daily life can enter the ocean as debris or particles. Driven by oceanic dynamics, it can travel long distances, leading to widespread marine plastic pollution[33]. Due to their stable, long-chain polymer structure, plastics are highly resistant to degradation in the environment. Their breakdown into smaller particles under the influence of light, physical, chemical, or biological factors is extremely slow and prolonged[34]. Once plastics are fragmented into microplastics, their physical and photodegradation processes are further diminished, causing them to accumulate in soils or sediments and persist in the environment for centuries to millennia[35]. Consequently, microplastics have garnered increasing attention as a novel class of persistent environmental pollutants.

Environmental plastic particles with a diameter of less than 5 mm are commonly defined as microplastics[36]. Microplastics, due to their chemical stability, persist in the environment for extended periods, classifying them as a novel environmental pollutant[37]. In marine ecosystems, they are categorized into primary and secondary microplastics[38]. The chemical composition of typical marine microplastics includes various polymers, such as thermoplastic polyester (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and polyamide (PA)[39].

Within the marine realm, microplastics are subjected to various transport and transformation mechanisms[40]. Microplastics, being less dense than seawater, typically float or remain suspended upon entering the ocean. They are then dispersed by dynamic forces such as ocean currents, tides, wind, waves, and tsunamis[41]. Among these forces, waves and tides are particularly significant in driving the deposition of microplastics in coastal regions. With prolonged exposure to the marine environment, the surface characteristics of hydrophobic microplastics become increasingly complex. These particles readily adsorb various organic and metallic pollutants and can also attach to clay particles, organic fragments, seaweed, and microorganisms[42]. These interactions can either increase the density of microplastic particles or modify their surface properties, ultimately promoting their sedimentation.

Within the marine environment, prolonged interactions among physical, chemical, and biological processes can cause microplastics to fragment into smaller particles at the nanoscale. Driven by solar radiation, marine biota, and seawater, microplastics are subjected to various degradation and transformation mechanisms, such as photodegradation, biodegradation, oxidative decomposition, and hydrolysis[43]. Additionally, microplastics are ingested by marine organisms and can be transported through the marine food web, thereby integrating into the marine biogeochemical cycles [44].

5. Impacts of microplastics on coral reef ecosystems

5.1 Effects of microplastics on corals

It is estimated that around 11.1 billion plastic items are entangled in coral reefs across the Asia-Pacific region, and this figure is expected to increase by 40% by 2025[45]. Coastal ecosystems, such as offshore coral reefs, may be disproportionately affected by microplastics as plastics of terrestrial origin break up and enter the marine environment [46].

5.1.1 Effects of microplastics on coral feeding, growth and development

Microplastics have been reported to be ingested by corals at rates comparable to those observed in plankton[46]. Coral feeding behavior is generally non-selective; however, corals exhibit a preference for particles with a diameter of less than 400 μm[48]. Notably, common reef-building corals typically feed on particles within the size range of 10 to 100 μm [40]. Given that microplastics fall within this size range, it is plausible that corals may mistake microplastics for food, leading to their capture and ingestion[50]. Furthermore, microplastics can be transferred through the food web of coral reef ecosystems. Moreover, the influence of microplastics on deep-sea ecosystems, particularly deep-sea coral reefs dominated by cold-water corals, warrants further attention[51]. Studies have demonstrated that microplastics may pose a significant threat to coral reef sedimentation by inhibiting coral growth, thereby endangering the resilience of cold-water coral reefs and their associated biodiversity[52].

5.1.2 Effects of Microplastics on Coral Diseases

In recent years, human activities in coral reef areas have intensified, with tourism, fishing operations, and land-based sewage discharge contributing to the influx of substantial quantities of plastic debris into nearshore coral reef environments [53]. This increase in plastic pollution has been linked to a significant rise in the prevalence of coral diseases associated with rapid mortality. Specifically, the incidence of three major coral diseases—skeletal erosion band disease, white syndrome, and black band disease—has been shown to escalate dramatically when plastic debris comes into contact with coral tissues [54]. The probability of disease occurrence increases from 4% to 89% when corals are in contact with plastic debris, highlighting the detrimental impact of such pollution. Moreover, continuous contact with microplastics has been demonstrated to further exacerbate the likelihood of disease onset [55].

5.1.3 Effects of Microplastics on Coral Stress Resistance and Immune System

The impact of microplastics on reef-building corals has garnered significant attention . Exposure to microplastics has been shown to impair the stress resistance and immune system of reef-building corals [56]. Tang et al.[57] used Pocillopora damicornis to study the responses of reef-building corals to acute microplastic exposure. They found that while short-term exposure had limited impact on symbiont concentration and photosynthetic product transporters, it significantly weakened coral stress resistance and immune function, potentially increasing coral susceptibility to other stressors and altering coral reef community dynamics. Liao et al.[58] evaluated the changes in biomarkers in corals following exposure to microplastics. The stability of plastics, primarily composed of long-chain polymers, renders them highly resistant to environmental degradation, with their breakdown into smaller particles being a slow and prolonged process influenced by light, physical, chemical, and biological factors.

5.2 Effects of microplastics on other organisms in coral reef ecosystems

5.2.1 Effects of Microplastics on Algae

Microplastics significantly affect both planktonic algae and macroalgae. In the case of planktonic algae, different species exhibit diverse responses to microplastic exposure[59]. Marine planktonic algae can interact with microplastics to form isomers, which subsequently alter their photosynthetic efficiency and growth dynamics. Additionally, microplastics can penetrate the cell walls and membranes of planktonic algae, resulting in decreased chlorophyll concentrations[60]. For marine macroalgae, microplastics floating on the sea surface can create a shading effect that reduces sunlight penetration, thereby impacting algal photosynthesis. This shading effect may further lead to a decline in the self-purification capacity of the water body.

5.2.2 Effects of Microplastics on Benthic Organisms

Benthic organisms, such as sediment-dwelling worms, may ingest plastics contaminated with organic compounds, leading to a significant increase in the accumulation of these compounds within their bodies [61]. Microplastic fragments, which are similar in size to sand grains and plankton, are readily consumed by a wide range of benthic invertebrates that occupy the base of the food chain [62]. While the concentration of polyethylene plastic in the natural environment does not appear to affect the growth or survival of sea urchin larvae, the presence of microplastics in culture media has been shown to significantly reduce the feeding rates of copepods on algae [63].Microplastics can cause adverse effects in living organisms by blocking their digestive tracts, as these organisms are unable to degrade microplastics or eliminate the additives they contain. Additionally, microplastics can absorb and concentrate the toxicity of marine pollutants, further exacerbating their harmful effects. In addition to obstructing the digestive tract and impeding normal feeding, the ingestion of microplastics has also been shown to cause cellular and tissue damage in blue mussels and crustaceans. Li et al.[64] utilized 16S rRNA gene high-throughput sequencing to investigate the impact of microplastics on the gut microbiota of mussels. Their study compared the gut microbiota of mussels exposed to microplastics with those of unexposed mussels. The results indicated that, after 1, 3, and 6 weeks of microplastic treatment, significant changes occurred in the gut microbiota of the mussels, thereby demonstrating the effects of microplastic exposure on their gut microbiota. Fernández et al.[65] exposed mussels to two different concentrations of microplastics and examined the absorption, removal, and accumulation of microplastics by the digestive glands. Their findings revealed that, under high-concentration conditions, the uptake of microplastics increased. Furthermore, the removal efficiency of microplastics by mussels was comparable to that of similarly sized food particles (e.g., microalgae). However, the removal efficiency of smaller microplastics (with particle or fragment sizes in the range of 2–4 μm) was lower than that of larger microplastics. In contrast, larger microplastics (with diameters >10 mm) were removed more rapidly than smaller ones. A significant number of marine crustaceans have experienced marked declines in survival and reproductive success due to the ingestion of microplastics.

5.2.3 Effects of microplastics on coral reef fish

Many studies have reported on fish ingestion of marine microplastics, but few studies have focused on plastic pollution of coral reefs and reef fish.Microplastic contamination has been documented in various marine organisms, including fish species from coral reef ecosystems. Kroon et al. [66] collected 20 juvenile coral trout (Plectropomus leopardus) of uniform size from around four reef islands in Australia's Great Barrier Reef World Heritage Area. Upon visual examination under a stereomicroscope, microplastics were detected in these juvenile fish, highlighting the early-life exposure to such pollutants. Garnier et al.[67] examined the digestive tracts of 133 adult fish from coral reef seas and found that 28 fish (21%) had ingested microplastics. The number of ingested microplastic fragments per fish ranged from 1 to 3 pieces, with an average of 1.25 ± 0.13 pieces, and 70% of the fragments were less than 0.3 mm in size, highlighting the prevalence of microplastic ingestion among adult fish and the tendency for smaller particles to be more readily ingested. Critchell et al.[68] conducted both acute and chronic exposure experiments using Acanthochromis polyacanthus, a fish species commonly found in Indo-Pacific coral reefs. In these experiments, microplastic particles were used to replace food particles. The results indicated that the growth rate of fish exposed to microplastics was significantly slower compared to controls, with more pronounced effects observed at higher microplastic concentrations. At the end of the chronic exposure experiment, 19.6% of the fish had plastic fragments in their digestive tracts. Notably, at moderate plastic exposure concentrations ($0.055\ mg{\cdot}L^{-1}$), there was a trend towards higher microplastic intake. These findings suggest that microplastic exposure can have adverse effects on fish growth and health, particularly when exposure concentrations are elevated.

When plastics enter the ocean, they can inflict a range of adverse effects on marine organisms. These impacts extend beyond physical harm, such as entanglement, tissue abrasion, and intestinal blockage, to include the loading and subsequent release of toxic and harmful pollutants. This dual mechanism of harm poses significant threats to marine life.Currently, research on the adverse effects of microplastics on marine organisms primarily focuses on describing toxic phenomena.

6. Summary and Prospect

Marine microplastics have emerged as a novel and substantial threat to coral reef ecosystems, posing significant risks to these fragile environments. In recent years, the issue of marine microplastic pollution and its ecological impacts has garnered increasing global attention. However, research on microplastic pollution within coral reef ecosystems remains in its early stages, with many aspects still unexplored. Strengthening the prevention and monitoring of microplastic pollution in coral reef ecosystems is essential to safeguard these critical marine habitats and ensure the long-term health and resilience of coastal ecosystems.

To enhance our understanding and management of microplastic pollution in coral reef ecosystems, several key strategies have been proposed. First, establishing a comprehensive and effective long-term monitoring network for coral reef ecosystems is crucial. Microplastics should be integrated into the monitoring of environmental indicators in coral reef areas, and robust methods for microplastic monitoring should be developed. This includes identifying specific biomarkers to evaluate the impact of microplastic pollution on coral organisms.

Moreover, it is imperative to investigate the status of microplastic pollution in coral reef ecosystems across various marine regions. This involves elucidating the distribution, transport, and environmental fate of microplastics in coral reef waters, as well as analyzing the types and primary sources of microplastic pollution. Considering the characteristics of human activities in coastal areas, a comprehensive technical and methodological framework suitable for monitoring and source analysis of microplastic pollution in coral reef ecosystems should be established.

Finally, a multi-level ecological index system (covering population, individual, tissue and organ, cellular, and genetic levels) should be developed to conduct health risk assessments of microplastic pollution on coral reef ecosystems. Through these integrated efforts, we can deepen our understanding of microplastic pollution and develop effective strategies to mitigate its impacts on coral reef ecosystems.

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