Paul *et al. Blue Biotechnology* (2024) 1:6
https://doi.org/10.1186/s44315-024-00006-6

Blue Biotechnology

REVIEW

Open Access

Unveiling the effects of microplastics pollution on marine fauna

Sonali Paul[1], Somava Nath[2], Shreya Bhattacharjee[3] and Susmita Mukherjee[1*]

Abstract

Microplastics have emerged as a pervasive environmental concern, threatening the health and stability of marine ecosystems worldwide. Microplastics permeate marine environments through various sources, including fragmentation of larger plastic debris, industrial discharges, and urban runoff. Once introduced into the marine ecosystem, microplastics interact with many organisms across trophic levels, from zooplankton to top predators. Through ingestion, entanglement, and bioaccumulation, microplastics pose direct threats to marine organisms' health, reproductive success, and survival. Moreover, microplastics serve as vectors for persistent organic pollutants, leaching harmful chemicals into the marine environment and exacerbating toxicity risk for marine life. This study highlights the broader ecological implications of microplastic pollution, including disruptions of marine food chain, and degradation of essential habitats such as coral reefs and estuaries. By altering species interactions and habitat structure, microplastics can compromise the resilience and functioning of marine ecosystems, with far-reaching consequences for biodiversity and ecosystem services. With the increase in microplastics in the marine environment it is important to have control measures as well. Comprehensive strategies for managing microplastic pollution should incorporate a combination of conventional approaches, including reduction at the source and targeted interventions to enhance degradation.

Keywords Microplastic, Marine ecosystem, Habitat-destruction, Bioavailability, Trophic levels

Introduction

Plastic has become an integral part of modern life, serving diverse purposes across various sectors due to its unique properties such as strength, elasticity, durability, and lightweight nature [50]. Its versatility finds application in industries ranging from food and medical equipment production to electronics. However, the improper disposal of plastic has led to a significant accumulation of this synthetic, non-biodegradable material in the environment. Research has shed light not only on the adverse effects of plastic on human health but also on the presence of microplastics, with estimates suggesting between 4.8 and 12.7 million tons of plastic debris end up in the oceans annually [28, 30]. Microplastics (MP) are defined as plastic particles ranging from 1 μM to 5 mm in size [15] and present a complex challenge due to their varied dimensions, density, and chemical composition. Furthermore, there are even smaller plastic fragments with < 1 μm size constituting nanoplastics [27]. Researchers globally have identified synthetic compounds like polypropylene, polyethylene, polystyrene, polyvinyl chloride, and polyethylene terephthalate in marine water, underscoring the pervasive presence of microplastics in aquatic ecosystems [29]. The minute size of microplastics and nanoplastics poses a considerable threat to aquatic life due to their potential for ingestion, accumulation and amplification in marine organisms as well as accumulating other pollutants due to their surface to volume ratio.

*Correspondence:
Susmita Mukherjee
susmita.mukherjee@uem.edu.in
[1] Department of Biotechnology, Institute of Engineering & Management, University of Engineering & Management, New Tow, Action Area III, Kolkata, India
[2] Department of Biotechnology, SRM Institute of Science and Technology, Kancheepuram District, Kattankulathur, Tamil Nadu 603203, India
[3] Pharma Source, Life Science Networks, London, UK

Moreover, as these contaminated aquatic species are consumed as seafood, microplastics can easily enter the human body through the food chain. The global plastic production, estimated at 367 million metric tons in 2020, contributes to the presence of microplastics in marine systems, with human activities such as tourism and the operation of wastewater treatment facilities by municipalities and industries further exacerbating the issue [21].

The escalating levels of microplastics in various water bodies, encompassing rivers, ponds, lakes, and oceans, stem primarily from the expanding human population and the widespread availability of microplastics [52]. Additionally, a multitude of factors such as wind patterns, temperature variations, water currents, and the physical characteristics of microplastics including size, shape, density, and chemical composition, play a pivotal role in the dispersion and proliferation of these synthetic materials within aquatic environments [18, 23]. Microplastics have been detected in diverse samples ranging from soil and deep seawater to polar regions, coastal areas, and surface water, highlighting the extensive contamination of various ecosystems. Studies revealed that the accumulation of microplastics in a wide array of aquatic organisms, including copepods, amphipods, sea cucumbers, fish, turtles, and birds, which inadvertently ingest these particles through their diet. Researchers worldwide have investigated the fate of ingested microplastics and observed that they can accumulate in specific human tissues, be excreted through pseudo-faeces, or migrate throughout various organs in the body [39, 40, 48]. Plasticosis is a recently discovered condition characterized by fibrosis, which is caused by the consumption of plastic, this condition mostly affects seabirds [14]. This disorder results in significant gastrointestinal harm, including inflammation, fibrosis, and scarring in the digestive system, which adversely affects the birds' capacity to process food, assimilate nutrients, and combat infections [19]. Researchers examining the impact of plastic pollution on animals introduced the term "plasticosis" to emphasize the detrimental effects of plastic consumption on seabirds. Plasticosis is associated with the consumption of microplastics, which may result in significant harm to tissues, disruption of tissue structure, and decreased flexibility of the stomach [37]. This eventually leads to hunger and detrimental effects on the development and survival of young birds. Plasticosis is a notable indication of the harmful impact of plastic pollution on marine ecosystems and animals. This highlights the pressing need to tackle plastic waste in order to avoid more damage to seabirds and other creatures. The accumulation of microplastics in bodily tissues can lead to detrimental health effects in organisms such as reproductive issues, stunted growth, internal or external injuries, and blockages in bodily passages, underscoring the multifaceted impacts of microplastic pollution on both wildlife and human health.

This phenomenon can lead to the bioaccumulation of a diverse array of substances in the water, including heavy metals, dyes, and hydrocarbons [5]. Consequently, the overall toxicity of marine ecosystems may be heightened by the presence of these additional harmful compounds. Considering all available information, it is clear that microplastics have emerged as significant pollutants in the twenty-first century, posing a substantial threat to aquatic life and ecosystem health due to their role in pollutant transport and bioaccumulation processes.

This study endeavours to uncover the intricate web of impacts that microplastics impose on marine environments, encompassing ecological, biological, and environmental dimensions. It has dealt with the impact of microplastics on marine fauna and ecological habitats, also focuses on the degradation mechanisms and control measures. The paper aims to identify the global threat of microplastics on the marine environment and propose avenues for future research to address this problem and develop efficient and effective combative strategies.

Characterization of microplastic

Microplastics can have varied shapes, sizes, colour, composition and monomer structure. Based on the characteristics, they can have different physical and chemical properties which can determine their distribution and accumulation. These properties determine their stability to persist in the nature in abundance and determine the food habit of the fishes and in turn how they affect the fish and the ecosystem.

One of the major physical properties which are studied to understand the nature of MPs is their size which ranges from 0-500 μm. Microplastics also vary in their shapes like they can be elongated fibres, irregular fragments or round spherical pellets based on their use in the industries and daily life [25]. MPs can act as micro-vector for minerals like orthoclase, carbon and microcline, also for pigments like vine black and dye like saffron can be found attached to them leading to further health hazard and toxicity. The major type of plastic monomer which form the MPs are Polyethylene (PE) (high and low density), poly(ethylene-co-1-hexene) (PEH), polypropylene (PP), polyurethane foam (PU), and poly (ethylene-co-vinyl acetate) (PEVA) [36]. Based on their composition, the density of microplastics can be varied as well. The density range can be from 0.91 g cm^{-3} for LDPE to 1.38 g cm^{-3} for PVC. Though Polystyrene has density of 1.05 g cm^{-3} whereas polypropylene has 0.85 g cm^{-3}. The different colours of MPs due to their origin can affect the food behaviour of the fishes. They can be of blue, white, green colour or can be also transparent. Temperature plays an important role over the structure of MPs.

Sources of microplastics

Microplastics have different anthropogenic origin such as fishing, aqua tourism and more [27]. Plastic manufacturing companies play a huge role in plastic contamination of the marine environment by the production of plastic pellets and resins from air blasting. Based on their size, they can be divided into two types [13]: Primary microplastic that are micro-sized synthetic plastics of the size < 2 mm (Table 1). These are generally found in personal care products in the form of microbeads, plastic pellets used in industrial manufacturing and transportation, and in synthetic textiles. They enter directly into the environment through various ways- wash of product use, unintentional loss from spills from industry or abrasion during washing of textiles [1]. Secondary microplastic are the broken fragments of larger macro or meso plastic, generally occurs when plastic undergoes weathering or is exposed under UV or to wind abrasion or water waves or some other environmental events like thermo-oxidative degradation, thermal degradation and hydrolysis [46] (Fig. 1). There are nanoplastics which has a size of < 1 µm size and has the potential to cause bioamplification and bioaccumulation of various pollutants because of their huge surface area [27].

Table 1 Microplastic and their sources

Type of Microplastic	Sources and Application
Polyethylene	Plastic bags, containers and wraps
Polypropylene	Plaastic bottles and ropes
Polystyrene	Food packaging industry and cutlery
Polyvinyl chloride	Pipes, cables, window frames and electrical goods
Polyamide	Textile industry and fishing industry

Bioavailability of microplastic through the trophic levels

Fishes are most vulnerable to MP depending on their eating behaviours and several other circumstances. It is seen that omnivorous fishes ingest the highest amount of MPs in comparison to plant-eating or carnivore fish. As MPs look alike the natural prey of the visual eaters, they are more likely to ingest the white MPs rather than red and black particles [11]. The MPs on which most of the fishes ingest are of the size of planktons in the range of 1–2.79 mm. Density of MPs determine their positioning and the type of fish that ingest them. Like Pelagic fishes eat low-density MPs whereas Demersal fish are prone to high-density MPs [12]. There are many more fundamental factors effecting the interaction methods of MPs and fishes which are still unclear [43].

Once the MPs are ingested by the fish, it can lead to biomagnification through the trophic levels [7]. The small planktivorous fishes when ingested by the bigger predatory fish lead to increase in concentration of MPs in their body. Though low-density MPs can be expelled of the

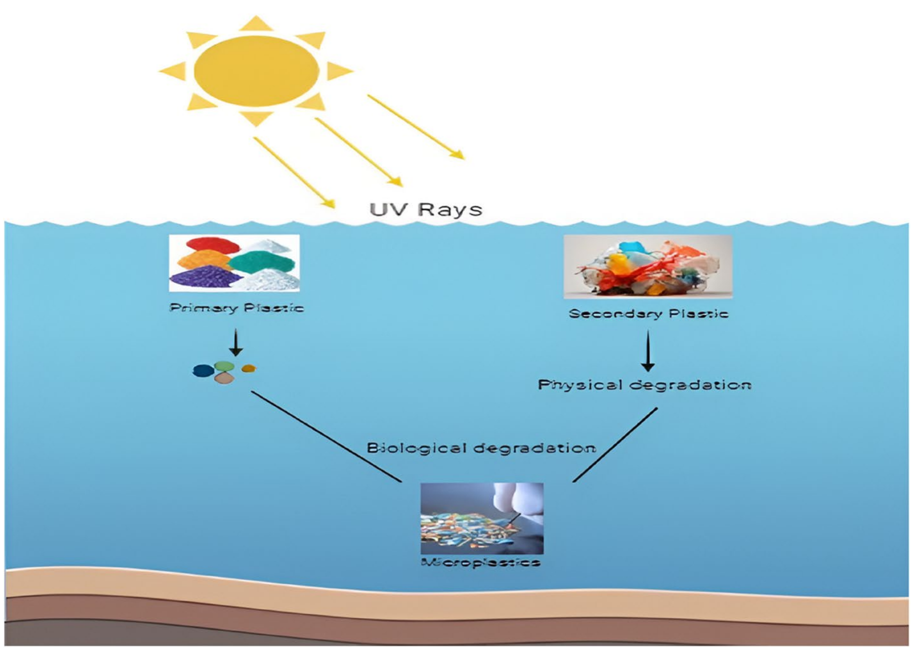

Fig. 1 Represents the conversion of primary and secondary plastics to microplastics

body of the fish by pseudo faeces, still most of the MPs remain in their gastrointestinal tract. For example, biomagnification can be seen in Tuna and Swordfish in the Mediterranean Sea.

The way biomagnification occurs in the fishes, it can also work in humans through the fishes in the same way (Fig. 2). The presence of MPs in the seafood poses a major hazard to human health, for example, it can cause oxidative stress and cytotoxicity [4, 31]. Endocytosis and persorption are the two major ways for MPs to enter the body, they can at first get concentrated in the intestinal system and then spread to other regions of the body leading to changes in metabolism and energy flow [9]. Microplastics have the potential to act as carriers, facilitating the binding and transportation of various pollutants into marine environments as shown in Fig. 2.

Effect on marine Fauna

Invertebrates

The presence of microplastics in aquatic environments poses a significant threat to marine ecosystems. Algae, including species like Chlorella sp, Scenedesmus, and Dunaliella sp, are fundamental components of aquatic food webs, serving as primary producers and providing energy for various marine organisms [22]. However, the accumulation of microplastics in algae can disrupt their normal physiological functions and ultimately impact the entire ecosystem. One of the primary mechanisms through which microplastics affect algae is through their physical and chemical properties. Microplastics are often positively charged due to their surface properties, while algae tend to carry a negative charge. This difference in charge facilitates the adsorption and accumulation of microplastics onto the surfaces of algae cells. As a result, microplastics can interfere with essential processes in algae, such as photosynthesis and growth [45].

The reduced photosynthetic activity is a common consequence of microplastic exposure in algae. Photosynthesis is a vital process through which algae convert light energy into chemical energy, which is essential for their growth and survival. However, the presence of microplastics can obstruct light penetration and disrupt the biochemical pathways involved in photosynthesis. This disruption leads to decreased photosynthetic efficiency and, consequently, reduced biomass production in algae populations.

The accumulation of microplastics can induce oxidative stress in algae cells. Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the antioxidant defence mechanisms within cells [16]. Microplastics can trigger the generation of ROS in algae, leading to oxidative damage to cellular components such as lipids, proteins, and DNA. This oxidative damage can impair cellular functions and compromise the overall health and viability of algae populations. The consequences of microplastic-induced alterations in algae extend beyond the algae themselves and can have cascading effects throughout the marine ecosystem [31]. Algae serve as a primary food source for various marine organisms, including zooplankton, fish, and marine mammals. Therefore, any decline in algae biomass resulting from microplastic exposure can disrupt food webs and impact the abundance and distribution of higher trophic levels.

Vertebrates

The impact of microplastics on fish species from various water sources has been extensively studied by researchers. Studies have shown a direct link between the presence of microplastics in fish samples collected from urbanized freshwater streams. Research has revealed the ingestion of microplastics and the presence of hard

Fig. 2 Transportation of micro plastics through marine environment different trophic levels (biomagnification)

fragments and fibers in the stomach cells of over 100 fish species, particularly in areas close to urban populations [8]. The toxic nature of microplastics is exacerbated by the presence of additives like dyes, heavy metals, and chemical compounds, leading to adverse effects on fish health, including inflammation, altered enzyme activity, metabolic changes, and even gene expression alterations [35]. Fish samples from urban areas exhibit higher concentration of microplastics compared to non-urbanized samples, underscoring the role of human activities in microplastic pollution. Furthermore, microplastics have been found in marine cetaceans such as whales and dolphins, causing chronic and acute toxicity by blocking filtering apparatuses [24] documented the presence of microplastics in dolphin stomachs. Various synthetic polymers, including nylon, polyvinyl chloride, and polystyrene, of diverse shapes and sizes have been identified in the intestines of Megaptera sp. [10]. The ingestion of these microplastics by cetacean species can result in both chronic and acute toxicity. Additionally, studies indicate that microplastics can obstruct the filtering mechanisms of marine organisms such as *Balaenoptera Physalus L*. Ingestion of microplastics by marine turtles has also been documented [38]. Common toxic effects of microplastic ingestion in turtles include severe damage and blockage of the digestive tract, reduced stomach capacity, and mortality. Other adverse effects include alterations in swimming behavior, immune response, growth rate, and prey avoidance capacity, all of which significantly impact marine turtle populations. Plastic debris can also have impact on environmental factors such as habitat temperature, negatively influencing the reproductive capacity of marine vertebrates. Plastic debris accumulated on the beach are seen to increase the temperature by making the sand warmer than the clean beaches. It in turn influence the behaviour of organisms living there. Also it impacts the behaviour of the organisms which have temperature dependent sex- determination.

Effect on ecological habitat

Coastal habitats, coral reefs and estuarine habitats are gravely affected by microplastic pollution [50]. Coastal habitats being the first to encounter the microplastics are the most vulnerable. It includes beaches, rocky shores, and salt marshes. As the shorelines acts as nurses for many marine species, microplastic pollution can impact the development and survival of the young organisms. Coral reefs being the hotspot of marine life diversity has a major role in the marine ecosystem [22]. Microplastics pose a great threat to the coral reefs by causing physical damage to the coral tissues leading to disease and bleaching. Hence there is a habitat loss for the species living in and around the coral reef. Estuarian regions support a diversity of species and ecosystem and are very susceptible to microplastic pollution as they are close to urban area and industrial activities [41, 49]. Microplastics can accumulate in the sediments of these regions unbalancing the ecosystem function. These habitat regions are important for commercially valuable fresh water and salt water fishes for their reproduction [35]. The contamination of waterways by microplastics (MPs) can lead to the presence of MPs in the raw materials used to produce commercial salts [32, 33]. This is concerning because salt is an essential nutrient for humans and a common food additive, so the potential exposure to MPs through salt ingestion should not be underestimated. A global review has concluded that the main types of MPs found in commercial salts are polypropylene (PP), which is highly abundant in European and Asian salts, and polyethylene (PE), which is prevalent in Oceanian, South American, and North American salts [42]. Hence presence of microplastic can affect the marine food web as well.

Degradation and control of microplastic

In the past, conventional methods were employed to remove microplastics (MPs) from the environment. Additionally, gathering plastic waste from beaches, including items like containers, bags, and bins, can reduce the influx of plastics into rivers and oceans, thereby preventing the formation of secondary MPs. Sustainable solutions for eliminating accumulated plastics are lacking. Traditional waste treatment methods such as incineration or landfilling are unsuitable for addressing the challenge of MP degradation. Although incineration effectively processes plastic waste, it also significantly contributes to greenhouse gas emissions like CO_2, CH_4, and CO [51]. Landfilling not only consumes large land resources but also raises concerns about chemical releases such as plasticizers and dyes, as well as soil depletion. In recent years, various innovative approaches have been proposed to address the immediate issue of MPs [3].

Advanced oxidation processes (AOPs) and biological decomposition represent two emerging options under investigation for the degradation of microplastics (MPs). These techniques break down the molecular bonds of MPs, reducing them into smaller molecules that can be converted into harmless by-products or completely oxidized into CO_2 and H_2O [47]. The specific by-products and mechanisms of breakdown depend on the composition of the polymer, which is in turn influenced by environmental factors. The process of polymer chain breakdown cannot be predicted and can occur at any monomer within the polymer. As a result, the cracking of MPs happens at the ends of monomer repeats, with the remaining monomers subsequently breaking down through a process known as chain depolymerization [17]. Abiotic degradation processes such as AOPs precede biological deterioration and are triggered by factors like heat, water, or UV-light exposure in natural settings [6]. As a result of abiotic breakdown, smaller plastic fragments are formed, which can permeate through biological membranes and be broken down by metabolic enzymes within various organisms. However, certain organisms release exoenzymes capable of targeting specific types of plastic polymers. Initially, most microplastics disintegrate on their exposed surfaces, which are susceptible to chemical and enzymatic actions. Consequently, microplastics degrade faster than larger plastic pieces due to their higher surface-to-volume ratio. The changes in color and the appearance of surface cracks serve as initial signs of polymer disintegration. Surface cracking facilitates further degradation of the microplastic material, leading to brittle fractures and eventual breakdown [20].

The degradation of microplastics (MPs) in the environment results from both biotic and abiotic processes. Biotic degradation involves living organisms such as bacteria, fungi, and microorganisms breaking down MPs enzymatically into smaller fragments [51]. On the other hand, abiotic degradation, also known as non-biological degradation, occurs through physical weathering, hydrolysis, and photochemical reactions induced by factors like sunlight (UV radiation), temperature variations, mechanical stress, and chemical reactions [6]. One advantage of biotic degradation is its selective nature, where certain bacteria can target and degrade particular types of MPs. Since microbes naturally exist in the environment and have evolved mechanisms for breaking down organic materials, biotic degradation mimics natural processes [47]. In certain conditions, microbial action can accelerate the breakdown of MPs, expediting the cleanup process. However, the effectiveness of biotic degradation is influenced by environmental factors such as temperature, pH, nutrient availability, oxygen levels, and others, which must be optimized for efficient degradation [51]. The biotic degradation also has drawbacks. The effectiveness of microbial breakdown depends on the specific environmental conditions and the types of microorganisms present. Some MPs may exhibit resistance to natural microbial degradation. Additionally, scaling up biotic degradation processes to manage large quantities of environmental MPs can be costly and technically challenging.

Therefore, comprehensive strategies for managing microplastic pollution should incorporate a combination of approaches, including reduction at the source, improved waste management, and targeted interventions to enhance degradation where feasible in order to have proper control over the usage of plastic.

In the "16th Global Meeting of the Regional Seas Conventions and Action Plans", the major concerned raised was the substantial increase of availability of plastic to marine ecosystem by the end of 2025 [26]. To combat this issue the States needs to literate the society about the harmful effect of plastic wastes [46]. New policies and strong legislative rules should be enforced to keep the use of plastics in check. The The United Nations Environment Assembly (UNEA) passed a resolution "UN Global Plastics Treaty (2022)" to develop a legally binding international treaty to combat plastic pollution and aiming to enhance global cooperation on technology and capacity building for managing plastic waste. In the developing countries heavy restrictions and bans are put on the use of plastic bags, bottles and other goods made of low-grade plastic (Plastic pollution coalition 2017). India enacted a comprehensive ban on single-use plastics to promote the use of sustainable and biodegradable alternatives addressing the issue of plastic pollution. However, sadly the FMCGs still continue using plastics in their products like toothpaste as well in the packaging of those products. Strict judicial actions should be taken against such companies which do not follow the protocol. Schemes like Extended Producer Responsibility (EPR) which encourage manufacturers to use packaging materials other than plastic should be strictly enforced. Moreover, scientific inventions and innovations can also facilitate produce environment friendly alternatives of plastics ofr different usage.

Future perspective

The issue of microplastics in marine environments necessitates a multifaceted approach that incorporates scientific inquiry, technological advancement, policy enactment, and community involvement. Developing standardized procedures to collect and examine small fragments of plastic in the ocean and coastal areas is essential for gaining accurate insights into their global abundance, distribution, and characteristics [2]. This standardized approach is vital for effective management strategies aimed at mitigating their impact. It is crucial to bridge the gap between laboratory experiments and real-world applications by conducting extensive, long-term field studies. These studies can provide valuable insights into how pollutants interact with microplastics over time in natural environments [44]. Further research is required to understand the mechanisms underlying the sorption of pollutants onto microplastics and to evaluate the potential risks and fate of microplastics in diverse environmental settings. Exploring the interactions between microplastics and a wider array of pollutants, such as radioactive heavy metals and antibiotics, is also critical. Comprehensive studies are necessary to assess the risks posed by microplastics to marine organisms and human health. This includes investigating how microplastics may serve as vectors for transporting harmful pollutants through marine food webs. Recent studies have concentrated on the advancement of biodegradable polymers and the utilization of microbial techniques to hasten the breakdown of plastic waste in composting facilities. Biodegradable polymers, derived from sources like starch or cellulose, have been engineered to be more easily decomposed by microorganisms than traditional petrochemical-based plastics. Concurrently, scientists have been pinpointing specific microbial strains and enzymes that can enhance the degradation of these biodegradable plastics during composting. The objective is to establish a harmonious system where biodegradable plastics can be efficiently composted alongside other organic waste, thereby diminishing the environmental repercussions of plastic pollution [34]. Ultimately, these research endeavours are vital for informing effective mitigation strategies and guiding policy decisions aimed at safeguarding marine ecosystems and human well-being.

Conclusion

The widespread global usage of plastics has led to the pervasive presence of microplastics across various environmental domains. Research indicates that these tiny plastic particles originate from diverse sources and follow multiple pathways before ultimately reaching the oceans, where they disperse both horizontally and vertically. Given their detrimental impact on marine ecosystems, including their ability to harm marine life by accumulation in organisms through food chains, addressing this has become imperative. Despite numerous strategies to combat marine microplastic pollution, none alone is sufficient. Hence, there is a pressing need for ongoing research to innovate and develop advanced or unconventional technologies capable of effectively removing microplastics from marine ecosystem.

Acknowledgements
The authors are grateful to the management of University of Engineering and Management Kolkata for providing the requisite support for this work

Authors' contributions
Susmita Mukherjee, corresponding author: Conceptualizing & Finalizing the manuscript. Sonali Paul: Drafting the manuscript. Shreya Bhattacharjee & Somava Nath: data mining and contributed in writing the draft manuscript

Funding
This work did not receive any funding.

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
The authors have consent to publish.

Competing interests
The authors declare no competing interests.

Received: 12 April 2024 Accepted: 29 June 2024
Published online: 13 September 2024

References

1. Abarghouei S, Hedayati A, Raeisi M, Hadavand BS, Rezaei H, Abed-Elmdoust A. Size-dependent effects of microplastic on uptake, immune system, related gene expression and histopathology of goldfish (Carassius auratus). Chemosphere. 2021;276: 129977. https://doi.org/10.1016/j.chemosphere.2021.129977.
2. Abreu A, Pedrotti ML. Microplastics in the oceans: The solutions lie on land. Field Actions Sci Rep (Special Issue 19):2019:62–67. Available at: http://journals.openedition.org/factsreports/5290.
3. Agarwal, S. Biodegradable polymers: present opportunities and challenges in providing a microplastic-free environment. Macromol. Chem. Phys. 2020:221 https://doi.org/10.1002/macp.202000017.
4. Alimba CG, Faggio C. Microplastics in the marine environment: Current trends in environmental pollution and mechanisms of toxicological profile. Environ Toxicol Pharmacol. 2019;68:61–74. https://doi.org/10.1016/j.etap.2019.03.001.
5. Amelia TSM, Khalik WMAWM, Ong MC, Shao YT, Pan HJ, Bhubalan K. Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. Progr Earth Planet Sci. 2021;8(1):1–26.
6. Andrady AL. Microplastics in the marine environment. Mar Pollut Bull. 2011;62:1596–605. https://doi.org/10.1016/j.marpolbul.2011.05.030.
7. Aragaw TA., and Mekonnen BA. Distribution and Impact of Microplastics in the Aquatic Systems: A Review of Ecotoxicological Effects on Biota. Microplastic Pollution. Sustainable Textiles: Production, Processing, Manufacturing & Chemistry. Springer Singapore, 2021:65–104. https://doi.org/10.1007/978-981-16-0297-9_3.
8. Ašmonaitė G, Tivefälth M, Westberg E, Magnér J, Backhaus T, Carney Almroth B. MPs as a vector for exposure to hydrophobic organic chemicals in fish: A comparison of two polymers and silica particles spiked with three model compounds. Front Environ Sci. 2020;8:87.
9. Barboza LGA, Vieira LR, Branco V, Figueiredo N, Carvalho F, Carvalho C, et al. Microplastics cause neurotoxicity, oxidative damage and energy-related changes and interact with the bioaccumulation of mercury in the european seabass, dicentrarchus labrax (Linnaeus, 1758). Aquat Toxicol. 2018;195:49–57. https://doi.org/10.1016/j.aquatox.2017.12.008.
10. Besseling E, Foekema EM, Van Franeker JA, Leopold MF, Kühn S, Bravo Rebolledo EL, Heße E, Mielke L, IJzer, J., Kamminga, P., Koelmans, A.A. Microplastic in a macro filter feeder: humpback whale Megaptera novaeangliae. Mar Pollut Bull. 2015;95(1):248–52. https://doi.org/10.1016/j.marpolbul.2015.04.007.
11. Borrelle SB, Ringma J, Law KL, Monnahan CC, Lebreton L, McGivern A, Murphy E, Jambeck J, Leonard GH, Hilleary MA, Eriksen M, Possingham HP, De Frond H, Gerber LR, Polidoro B, Tahir A, Bernard M, Mallos N, Barnes M, Rochman CM. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science. 2020;369(6510):1515–8. https://doi.org/10.1126/science.aba3656.
12. Braeuning A. Uptake of microplastics and related health effects: a critical discussion of Deng et al., Scientific reports 7:46687, 2017. Arch Toxicolarchives Toxicol. 2019;793(1):46687219–46687220. https://doi.org/10.1007/s00204-018-2367-9.
13. Carlo Giacomo Avio, Stefania Gorbi and Francesco Regoli, Plastics and microplastics in the oceans: From emerging pollutants to emerged threat, Marine Environmental Research, Doi.org/https://doi.org/10.1016/j.marenvres.2016.05.012, 2016.
14. Charlton-Howard HS, Bond AL, Rivers-Auty J, Lavers JL. 'Plasticosis': Characterising macro- and microplastic-associated fibrosis in seabird tissues. J Hazard Mater. 2023;450: 131090. https://doi.org/10.1016/j.jhazmat.2023.131090.

15. Cole M, Lindeque P, Halsband C., Galloway TS. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 2011;62(12):2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.
16. Das A. The emerging role of microplastics in systemic toxicity: involvement of reactive oxygen species (ROS). Sci Total Environ. 2023:165076. https://doi.org/10.1016/j.scitotenv.2023.165076.
17. Du H, Xie Y, Wang J. Microplastic degradation methods and corresponding degradation mechanism: research status and future perspectives. J Hazard Mater. 2021;418: 126377. https://doi.org/10.1016/j.jhazmat.2021.126377.
18. Duis K, Coors A. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ Sci Eur. 2016. https://doi.org/10.1186/s12302-015-0069-y.
19. Fackelmann G, Pham CK, Rodríguez Y, Mallory ML, Provencher JF, Baak JE, Sommer S. Current levels of microplastic pollution impact wild seabird gut microbiomes. Nat Ecol Evol. 2023;7(5):698–706.
20. Gewert B, Plassmann MM, Macleod M. Pathways for degradation of plastic polymers floating in the marine environment. Environ Sci Process Impacts. 2015;17:1513–21. https://doi.org/10.1039/c5em00207a.
21. Gola D, Tyagi PK, Arya A, Chauhan N, Agarwal M, Singh SK, Gola S. The impact of microplastics on marine environment: A review. Environ Nanotechnol Monitor Manage. 2021;16: 100552.
22. Green DS. Effects of microplastics on European flat oysters, Ostrea edulis and their associated benthic communities. Environ. Pollut. 2016;216:95–103. https://doi.org/10.1016/j.envpol.2016.05.043.
23. Guzzetti E, Sureda A, Tejada S, Faggio C. Microplastic in marine organism: Environmental and toxicological effects. Environ Toxicol Pharmacol. 2018. https://doi.org/10.1016/j.etap.2018.10.009.
24. Hernandez-Gonzalez A, Saavedra C, Gago J, Covelo P, Santos MB, Pierce GJ. Microplastics in the stomach contents of common dolphin (Delphinus delphis) stranded on the Galician coasts (NW Spain, 2005–2010). Mar Pollut Bull. 2018;137:526–32. https://doi.org/10.1016/j.marpolbul.2018.10.026.
25. Irfan T, Khalid S, Taneez M, Hashmi MZ. Plastic driven pollution in Pakistan: the first evidence of environmental exposure to microplastic in sediments and water of Rawal Lake. Environ. Sci. Pollut. Res. 2020;27(13):15083–15092. https://doi.org/10.1007/s11356-020-07833-1.
26. Jenna R. Jambeck, Roland Geyer, Chris Wilcox,Theodore R. Siegler, Miriam Perryman, Anthony Andrady, Ramani Narayan, Kara Lavender Law, Plastic waste inputs from land into the ocean, Science. 2015. https://doi.org/10.1126/science.1260352.
27. Joso Pinto da Costa, Patricia S M Santos, Armando C Duarte and Teresa Rocha-Santos, (Nano)plastics in the environment – Sources, fates and effects, Science of the Total Environment. 2016:0048–9697. https://doi.org/10.1016/j.scitotenv.2016.05.041.
28. Kleme˘s, J.J., Fan, Y. Van, Jiang, P. Plastics: friends or foes? The circularity and plastic waste footprint. Energy Sources, Part A Recover. Util. Environ. Eff. 2020:1–17. https://doi.org/10.1080/15567036.2020.1801906.
29. Kor K, Mehdinia A. Neustonic microplastic pollution in the Persian Gulf. Mar Pollut Bull. 2020;150: 110665. https://doi.org/10.1016/j.marpolbul.2019.110665.
30. Kosior, E., Mitchell, J. In: Plastic Waste and Recycling. Elsevier. 200:133–162. https://doi.org/10.1016/B978-0-12-817880-5.00006-2.
31. Li K, Linsen Du, Qin C, Bolan N, Wang H, Wang H. Microplastic pollution as an environmental risk exacerbating the greenhouse effect and climate change: a review. Carbon Research. 2024. https://doi.org/10.1007/s44246-023-00097-7.
32. Kuttykattil A, Raju S, Vanka KS, Bhagwat G, Carbery M, Vincent SGT, ... & Palanisami T. Consuming microplastics? Investigation of commercial salts as a source of microplastics (MPs) in diet. Environ Sci Pollut Res . 2023;30(1):930–942.
33. Li T, Shi J, Liu X, He M, Wang J, Yan X, Fan Y. Analysis of the effect of salt processing on microplastic residues in crushed and washed sea salt. J Sea Res. 2023;194: 102405.
34. Lim BKH, San Thian E. Biodegradation of polymers in managing plastic waste—A review. Sci Total Environ. 2022;813: 151880.
35. Luís LG, Ferreira P, Fonte E, Oliveira M, Guilhermino L. Does the presence of microplastics influence the acute toxicity of chromium(VI) to early juveniles of the common goby (Pomatoschistus microps)? A study with juveniles from two wild estuarine populations. Aquat Toxicol. 2015;164:163–74. https://doi.org/10.1016/j.aquatox.2015.04.018.
36. Mataji A, Taleshi MS, Balimoghaddas E. Distribution and Characterization of Microplastics in Surface Waters and the Southern Caspian Sea Coasts Sediments. Arch Environ Contam Toxicol. 2020;78(1):86–93. https://doi.org/10.1007/s00244-019-00700-2).
37. Mills G. Plastic causing new disease of seabirds. Vet Record/the Vet Record. 2023;192(7):274–5. https://doi.org/10.1002/vetr.2907.
38. Nelms SE, Duncan EM, Broderick AC, Galloway TS, Godfrey MH, Hamann M, Lindeque PK, Godley BJ. Plastic and marine turtles: A review and call for research. ICES J Mar Sci. 2016. https://doi.org/10.1093/icesjms/fsv165.
39. Nie H, Wang J, Xu K, Huang Y, Yan M. Microplastic pollution in water and fish samples around Nanxun Reef in Nansha Islands. South China Sea Sci Total Environ. 2019;696: 134022. https://doi.org/10.1016/j.scitotenv.2019.134022.
40. Ogonowski M, Schür C, Jars´en, Å., Gorokhova, E., Mukherjee, A. The effects of natural and anthropogenic microparticles on individual fitness in daphnia magna. PLoS ONE. 2016;11(5): e0155063. https://doi.org/10.1371/journal.
41. Paterson DM, Defew EC, Jabour J. Ecosystem function and co-evolution of terminology in marine science and management. Marine biodiversity and ecosystem functioning. M. Solan, R. J. Aspden and D. M. Paterson, Oxford University Press. 2012;1:1–240.
42. Peixoto D, Pinheiro C, Amorim J, Oliva-Teles L, Guilhermino L, Vieira MN. Microplastic pollution in commercial salt for human consumption: A review. Estuar Coast Shelf Sci. 2019;219:161–8.
43. Sequeira IF, Prata JC, da Costa JP, Duarte AC, Rocha-Santos T. Worldwide contamination of fish with microplastics: a brief global overview. Mar Pollut Bull. 2020;160: 111681. https://doi.org/10.1016/j.marpolbul.2020.111681.
44. Sharma S, Bhardwaj A, Thakur M, Saini A. Understanding microplastic pollution of marine ecosystem: a review. Environ Sci Pollut Res. 2023:1–44. https://doi.org/10.1007/s11356-023-28314-1.
45. Shen M, Ye S, Zeng G, Zhang Y, Xing L, Tang W, … Liu S. (2019). Can microplastics pose a threat to ocean carbon sequestration? Marine Pollut Bull. 20109:110712. https://doi.org/10.1016/j.marpolbul.2019.110712.
46. Shivika Sharma and Subhankar Chatterjee, Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environ Sci Pollut Res. 2017.https://doi.org/10.1007/s11356-017-9910-8.
47. Silva AB, Costa MF, Duarte AC. Biotechnology advances for dealing with environmental pollution by micro(nano)plastics: lessons on theory and practices. Curr Opin Environ Sci Health. 2018;1:30–5. https://doi.org/10.1016/j.coesh.2017.10.005.
48. Sussarellu R, Suquet M, Thomas Y, Lambert C, Fabioux C, Pernet MEJ, Le Goïc N, Quillien V, Mingant C, Epelboin Y, Corporeau C, Guyomarch J, Robbens J, Paul-Pont I, Soudant P, Huvet A. Oyster reproduction is affected by exposure to polystyrene microplastics. Proc Natl Acad Sci U S A. 2016;113(9):2430–5. https://doi.org/10.1073/pnas.1519019113.
49. Törnroos A, Bonsdorff E, Bremner J, Blomqvist M, Josefson AB, Garcia C, et al. Marine benthic ecological functioning over decreasing taxonomic richness. J Sea Res. 2014. https://doi.org/10.1016/j.seares.2014.04.010.
50. Zhang D, Liu X, Huang W, Li J, Wang C, Zhang D, Zhang C. Microplastic pollution in deep-sea sediments and organisms of the Western Pacific Ocean. Environ Pollut. 2020;259: 113948. https://doi.org/10.1016/j.envpol.2020.113948.
51. Zhou D, Chen J, Wu J, Yang J, Wang H. Biodegradation and catalytic-chemical degradation strategies to mitigate microplastic pollution. Sustain Mater Technol. 2021;28: e00251. https://doi.org/10.1016/j.susmat.2021.e00251.
52. Zhou Q, Zhang H, Fu C, Zhou Y, Dai Z, Li Y, Tu C, Luo Y. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma. 2018;322:201–8. https://doi.org/10.1016/j.geoderma.2018.02.015.

Publisher's Note