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Microplastics: understanding the interaction with the food web and potential health hazards

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Microplastics have become a universal environmental contaminant, penetrating marine and freshwater ecosystems and presenting significant adverse effects on aquatic life and human health. In aquatic organisms, microplastics can cause physical harm, disrupt feeding and reproductive behaviours, and carry toxic chemicals that intensify their impact. For humans, the ingestion of microplastics through contaminated seafood and water raises concerns about long-term health complications, including inflammation, endocrine disruption, and exposure to harmful additives and pollutants associated with microplastics. The exploration of the origin of microplastics, their transport, and distribution at various trophic levels of the food web has become an imperative environmental concern. From filter-feeding zooplankton to predatory fish, microplastics are ingested and assimilated, with the potential for bioaccumulation and biomagnification along the food chain. Moreover, their small size and widespread dispersal make them particularly challenging to mitigate or eliminate from the environment. The present review underscores the necessity for ongoing research to fully elucidate the mechanisms and consequences of microplastic interactions within the food web. Enhanced understanding of these dynamics is crucial for developing effective mitigation strategies and regulatory policies aimed at reducing microplastic pollution and protecting ecosystem and human health.

Keywords: bioaccumulation/environment/environmental impact/food web/health and safety/human health/marine ecosystem/marine geotechnics/microplastics

Introduction

Plastic waste poses significant environmental challenges upon leakage into ecosystems, notably manifesting in the obstruction of waterways, thereby creating stagnant reservoirs conducive to the proliferation of disease vectors, including mosquitoes and other pests. This, in turn, facilitates the transmission of vector-borne diseases and amplifies the dissemination of toxic chemicals, ultimately disrupting the intricate balance of chief biogeochemical processes such as carbon, phosphorus, and phosphate cycles occurring within terrestrial ecosystems (Wang *et al.*, 2021). The interference of plastics into the food chain eventually results in causing detrimental effects and inherent risks to both fauna and humans alike. The ingestion of plastics by marine organisms, such as dolphins, turtles, and seabirds, results in respiratory pathway obstructions, triggering fatal consequences. Furthermore, larger plastic debris undergoes degradation through various interactions with the natural environment, encompassing physical, chemical, and biological mechanisms, including mechanical breakdown, biodegradation, thermal influences, UV exposure, photodegradation, and the exertion of mechanical forces such as friction and turbulence

(Corcoran, 2022; Wang *et al.*, 2019). This has led to the generation of another category of pollutant called microplastics (MPs).

In recent years, the pervasive issue of MP pollution has drawn significant attention from the scientific community, highlighting the urgent need to comprehend its consequences across ecological systems (Eze *et al.*, 2024). MPs are the tiny particles of plastic measuring less than 5 mm in size and have emerged as a substantial environmental concern (Napper and Thompson, 2020). While the upper limit of this spectrum is well established, the lower limit remains a topic of debate. Plastic particles in the nanometre range (smaller than 1 μm) are typically referred to as nanoplastics (NPs) due to their uniquely distinct behaviours. However, a precise definition for NPs has yet to be determined (Gigault *et al.*, 2018). MPs can enter the food web through various pathways and have the potential to interact with organisms at different trophic levels, leading to adverse effects on human health and ecosystem. These plastic particles harbour toxic chemicals with carcinogenic properties, impacting the nervous, reproductive, and respiratory systems (Kumar *et al.*, 2024). Several studies have claimed that MPs can impair feeding, growth, reproduction, and survival in various

organisms (Bhuyan, 2022; Blackburn and Green, 2022; Campanale *et al.*, 2020; Mallik *et al.*, 2021; Prata *et al.*, 2020). With MPs becoming more widespread, it is crucial to study how they move through food chains and their impacts on ecosystems.

In developing nations, the incineration of plastics for cooking and heating purposes results in prolonged exposure to hazardous emissions into environment. Also, plastic litter inflicts economic losses upon the global tourism, fishing, and shipping sectors. Consequently, the expense associated with the comprehensive remediation of plastics across diverse ecosystems appears financially untenable and prohibitive.

As plastics move up the food chain, the associated toxins can also migrate and accumulate in animals' fats and tissues, a process known as bioaccumulation (Carbery *et al.*, 2018). Furthermore, chemicals added to plastics during the manufacturing process to give them certain properties start leaching out even when inside the bodies of animals.

MPs, due to their small size, are recognised as physical, chemical, and biological stressors, exerting deleterious effects on critical ecosystem services and valuable resources, and contributing to climatic distress in marine ecosystems. The link between plastic pollution and climate change is evident; mechanisms such as photodegradation and denitrification worsen the climate change, amplifying the prevalence of MPs and precipitating eutrophication in aquatic environments. Recent studies allow researchers to better detect MPs, improving our understanding of their accumulation in organisms and transfer between various trophic levels (Anas *et al.*, 2024; Li *et al.*, 2024; Vaid *et al.*, 2024).

The relationship between MPs and various trophic organisms, spanning marine, terrestrial, and avian species, takes centre stage in our exploration regarding the source and route of exposure as well as translocation of MPs in the body. By analysing the latest research findings, this article aims to explore the complex interactions of MPs within various trophic networks and simultaneously consider their potential biomagnification and bioaccumulation along the food chain.

The polymer scenario

The chemical compounds, either naturally occurring or synthetic, having large-sized molecules, are formed by repeating interconnected units/links. Synthetic polymers include Teflon, polyester, epoxy, polyethylene, nylon, and so on, while silk, wool, and cellulose are some of the naturally occurring polymers. These polymers occur majorly in man-made materials. Plastic is yet another very commonly occurring polymer, comprising of homogeneously bound repeating units of monomer molecules (Li *et al.*, 2021). The properties of plastics include plasticity, low density, low or no electrical conductivity, transparency, toughness, and so on. These can be categorised into high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene

(PS), acrylonitrile-butadiene-styrene, polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), epoxies, and polycarbonate. Out of these plastic polymers, PP, PS, HDPE, and LDPE are the ones that account for the most abundantly occurring MPs (MacLeod *et al.*, 2021).

Plastics have multiple physico-chemical properties, and their use is more economical than other materials such as glass, metals, and ceramics (Beaumont *et al.*, 2019). Therefore, they are used in a number of applications, and as they are easy to process, it is also possible to manufacture plastic products in a variety of shapes. 'Plastic problem' arose with the manufacturing of several tonnes of 'single-use plastic', which in turn brought up the idea of the 'throw-away' culture. These plastics are derived and made from the petrochemical waste generated from the fossil fuel industries. The waste thus generated includes materials of high molecular mass from ethylene, propylene, and styrene (Lehel and Murphy, 2021). The presence of such chemicals poses significant challenges during production as well as degradation of plastic materials, as they lead to the release of several greenhouse gases and contribute to environmental pollution. The global primary plastic production by polymer has increased from a total production of 129.89–459.75 Mt from the year 1999–2019 (MacLeod *et al.*, 2021). The COVID-19 pandemic has increased the role of plastics in our daily lives (Shams *et al.*, 2021). Whether it be personal protective equipment or other disposable medical devices or packaging solutions, plastics are proving to be lifesaving due to their inherent properties in protecting the health and safety of frontline healthcare workers and the public during the pandemic. Plastic production alone accounted for 390.7 Mt during the pandemic (Parashar and Hait, 2021; Patrício Silva *et al.*, 2021). As the demand is continuously growing to meet the daily needs of consumers, it is estimated that the global annual production will reach 1.1 billion tonnes by 2050. The production of plastics has reached alarming levels, and the mismanagement of plastic waste is estimated to increase significantly in the coming years (Kumar *et al.*, 2021).

It is important to notice that as the plastic particles fragmentise into smaller particles such as NPs, there might be changes in their chemical and toxicological properties, which may affect their interactions with various biological systems. NPs may penetrate deeper into biological tissues and cellular membranes and potentially cause inflammatory responses and bioaccumulation in the food chain (Palmer and Herat, 2021). The natural environment, namely, oceans, rivers, and even the air we breathe, is becoming polluted with MPs and NPs and therefore disturbing the natural habitat (Keinänen *et al.*, 2021).

The alarming situation is that these tiny plastic particles have now been detected in diverse environments, including sediments, sewage, soil, fabrics, and so on (Kasmuri *et al.*, 2022), and even in tap water, bottled water, table salt, and seafood.

Studies have shown that MPs and NPs can enter the food chain and have the potential to impact the health of an organism to a great extent (Chormare and Kumar, 2022; Lehel and Murphy, 2021). The accidental ingestion of these particles by marine and freshwater organisms, as well as their accumulation in terrestrial plants and animals, raises concerns for the safety of our food and water sources. Furthermore, the transport of these particles in the atmosphere as ‘plastic rain’ or ‘plastic smog’ poses a risk to breathable air. Notably, MPs and NPs have the potential to significantly impact global biodiversity change (Chow *et al.*, 2023) and also serve as potential vectors for pathogens and toxic contaminants. Given the prevalence of these particles in various environments, it is imperative to further investigate their potential adverse effects on soil organisms and terrestrial ecosystems (Schmaltz *et al.*, 2020).

Generation of microplastics

The formation of MPs by fragmentation of larger plastic pieces in the marine environment is a complex process that depends on many factors, including brightness, temperature, oxygen content, and properties of the decay material such as molecular weight (Huber *et al.*, 2022). Environmental weathering has been observed to have a significant effect on the rate at which MPs are produced (Chormare and Kumar, 2022). The accumulation of MPs on the surface of the Atlantic Ocean alone is estimated to exceed 21 Mt (Xiao *et al.*, 2022). Considering the significant accumulation of MPs, it is crucial to understand their occurrence, fate, and transport pathways to better assess the associated risks and develop effective mitigation strategies (Cheng *et al.*, 2022).

Enhancing our comprehension of the impact of MPs on nature, including their harmful effects and function as carriers of additives and pollutants, emphasises the critical need to tackle this worldwide concern (Hu *et al.*, 2019). One potential source of MPs is the degradation of larger plastic items, such as bottles, bags, and packaging materials. In addition, MPs can be directly manufactured in specific forms for various purposes, such as exfoliants in personal care products or abrasives in industrial applications (Xiao *et al.*, 2022). Therefore, to accurately assess the presence and potential risks of MPs in the environment, it is essential to develop effective detection.

Escape of microplastics in the environment

Once the breakdown of commercially synthesised primary MPs occurs, secondary MPs (SMPs) are formed. SMPs are irregular plastic fragments resulting from the accidental breakage of larger plastic products, such as plastic bags, boxes, ropes, nets, and so on (Lehtiniemi *et al.*, 2018). The fragmentation or breakdown occurs over time due to ultraviolet radiation from the sun and mechanical influences, such as ocean waves (Laskar and Kumar, 2019; Pironti *et al.*, 2021). The SMPs are chemically toxic and, when released into the environment, cause several detrimental effects on various ecosystems, such as marine or aquatic, terrestrial, aerial, and so on, as shown in Figure 1. These small particles are often ingested by marine organisms, starting from the primary producers, such as phytoplankton, and further zooplankton, which acts as a link towards higher trophic levels, including fish and marine mammals, reaching up to the highest trophic level, that is, the tertiary consumers (Debnath *et al.*, 2022; Troost *et al.*, 2018). MPs can accumulate in the bodies of these organisms, leading to internal

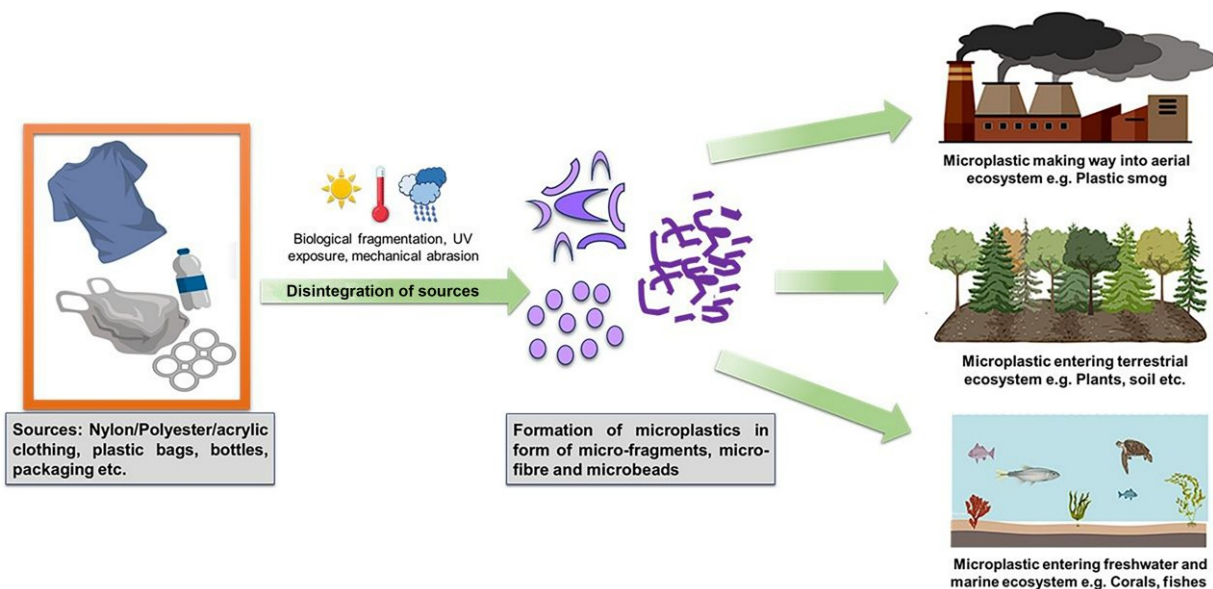


Figure 1. The origins and contributors to the breakdown of microplastics, as well as the mechanisms through which they infiltrate diverse ecological systems

blockages, starvation, breathing, and reproductive issues. This can have far-reaching consequences for the food chain and has the potential to affect different ecosystems. Furthermore, this can have implications for human health, as we consume seafood that may have ingested MPs. Furthermore, MPs can act as a vector for the spread of pathogens. The small size of MPs allows them to carry bacteria, viruses, and other harmful microorganisms, posing a risk to aquatic organisms and humans who rely on these ecosystems for food and several other recreational purposes (Yuan *et al.*, 2022b).

MPs are primarily adsorbers, utilising mechanisms such as hydrophobic interactions (Zhao *et al.*, 2022), Van der Waals forces (Zheng *et al.*, 2024), and chemical bonding (Hai *et al.*, 2020) to adhere pollutants onto their surfaces (Yu *et al.*, 2024). Pollutants often adhere to hydrophobic surfaces, including MPs, which act as vectors for transporting these contaminants. Studies have shown that MPs/NPs can sorb a variety of hydrophobic organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls, organochlorinated pesticides, heavy metals, and antibiotics due to their low polarity and affinity for these substances (Cássio *et al.*, 2022; Harmon, 2018; Koelmans *et al.*, 2016). The sorption process is influenced by environmental factors such as temperature, pH, and ionic strength (Cássio *et al.*, 2022). Furthermore, the interaction of MPs with these pollutants results in complex matrices and toxicological profiles, as demonstrated by Jiao *et al.* (2022).

In addition, the hydrophobic nature and substantial surface area of the MPs attract the contaminants, which are present in the dissolved state. Hydrophobicity plays a crucial role in the behaviour of pollutants in aquatic environments, particularly when these contaminants are in a dissolved state. This phenomenon is primarily driven by the interactions between hydrophobic substances and water, which significantly influence the bioavailability and toxicity of various pollutants. Hydrophobic molecules tend to cluster together in water to minimise their exposure to the aqueous environment. This aggregation can enhance the concentration of pollutants in localised areas, leading to higher toxicity levels for aquatic organisms (Meyer *et al.*, 2006). MPs not only adsorb these hydrophobic pollutants but also facilitate their movement through aquatic ecosystems. The dynamics of pollutant transfer from MPs to marine organisms have raised concerns regarding the increased exposure risks associated with plastic pollution (Koelmans *et al.*, 2016; Trevisan *et al.*, 2022).

The adsorption potential of MPs extends their impact beyond a singular pollutant, leading to intricate toxicity when interacting with other environmental contaminants (Kim *et al.*, 2021). The accumulation of hydrophobic pollutants in the tissues of aquatic organisms can lead to adverse health effects, including reproductive toxicity and disruption of endocrine systems. The bioaccumulation potential varies among species, depending on their feeding habits and habitat (Ashraf *et al.*, 2020; Trevisan *et al.*, 2022).

Many hydrophobic contaminants are persistent in the environment due to their low solubility in water. This persistence allows them to accumulate over time, posing long-term risks to aquatic ecosystems and potentially entering the food chain (Cássio *et al.*, 2022; Koelmans *et al.*, 2016). These investigations underscore the need for a holistic approach to assessing the environmental implications of MPs, considering their ability to interact with and transport an assortment of harmful substances.

Interference of microplastics within organisms and food web

MPs have been found to cause harm to hundreds of species, including sea turtle species, cetaceans, and marine bird species, and damage coral reefs and other ecosystems (Wang *et al.*, 2019). Furthermore, MPs have the potential to disrupt the food web and affect the overall health and population dynamics of species at various trophic levels within the food web (Carbery *et al.*, 2018). Therefore, it is crucial to further understand the sources, fate, and effects of MPs to mitigate their impact on organisms and the overall functioning of the food web.

The interaction of MPs with the food web is a multi-faceted issue that has acquired significant attention in recent years. MPs have been found to be widespread in terrestrial, aerial, and marine habitats, from the sea surface to the deep sea, and have been detected in various marine organisms, including zooplankton, fish, and top predators such as penguins (Bessa *et al.*, 2019; Cole *et al.*, 2014; Thompson, 2015). MPs can be ingested by marine organisms, indicating that species at lower trophic levels of the marine food web are mistaking plastic for food, raising concerns about potential risks to higher trophic level species (Desforges *et al.*, 2015; Kaposi *et al.*, 2014). Furthermore, the potential for MPs transfer through marine food webs has been assessed, with the evidence suggesting that MPs can infiltrate the food chain, potentially leading to bioaccumulation and biomagnification of these particles (McIlwraith *et al.*, 2021; Zhang *et al.*, 2020). This entire process creates a pathway for pollutants to move through the ecosystem (Lehel and Murphy, 2021).

While the ingestion of MPs by marine organisms has been well documented, the trophic magnification of MPs in the food web is still a topic of ongoing research to fully understand the potential impacts of MPs on the structure and functioning of food chains (Ding *et al.*, 2024). Figure 2 depicts how the SMPs make their way into the food web, starting from the primary producers (autotrophs) and moving up the higher trophic levels, affecting primary, secondary, tertiary consumers, and sometimes quaternary consumers, hence covering five trophic levels.

Three key ideas are utilised in ecological risk assessments (EcoRA): (a) bioconcentration, (b) bioaccumulation, and (c) biomagnification to ascertain the degree of pollution movement within the food chain (Chormare and Kumar, 2022). According to USEPA (1997), bioconcentration is defined as an increase in

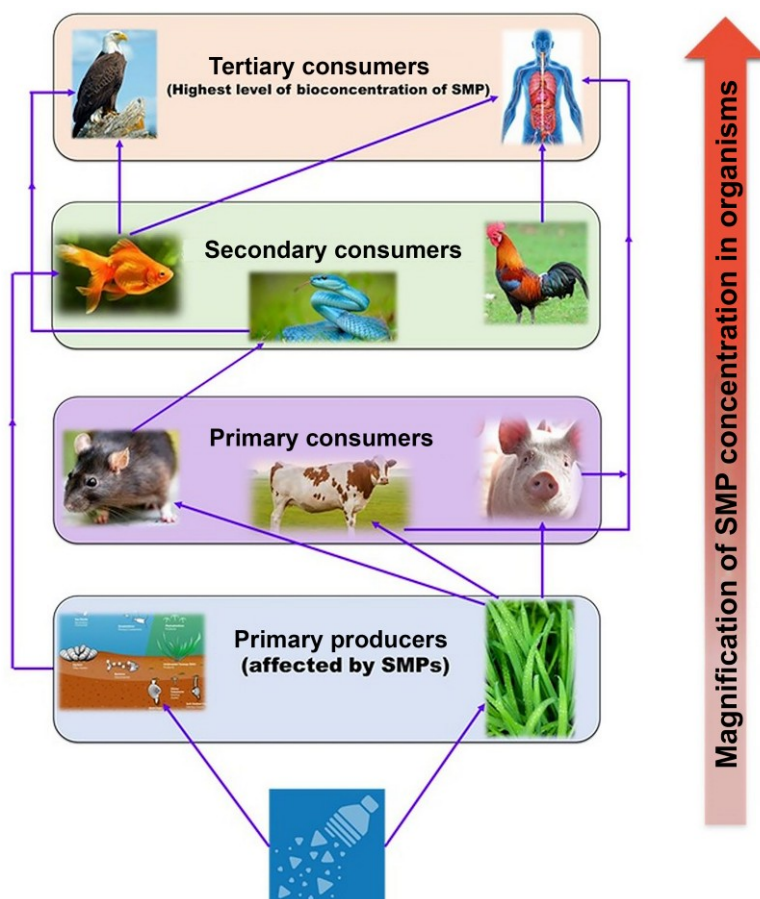


Figure 2. Interaction of SMPs at different trophic levels

pollution (such as MP in this case) within an organism compared with the concentration in the organism's surroundings. Biomagnification is the term used to describe the rise of a contaminant (such as MPs) in an organism relative to the concentration present in its prey. Ingestion of MPs by smaller organisms (plankton or small invertebrates), which are further consumed by larger ones, leads to the accumulation of MPs and hence, transference along the food chain. Over time, the concentration of MPs can become more concentrated in higher trophic levels, such as predatory fish or marine mammals. This process of biomagnification can also result in the transfer of any toxic chemicals or additives that are attached to the MPs. This can pose a threat to the organisms at the top of the food chain, including humans, as they may unknowingly consume these contaminated organisms (Miller *et al.*, 2023). Bioaccumulation is the net uptake of a pollutant (such as MPs) from the environment through all feasible pathways from any source (including water, sediment, and prey) (Miller *et al.*, 2023). Bioaccumulation occurs when an organism takes up a contaminant faster than it can excrete or metabolise it. This means that over time, MPs and any associated contaminants can build up in an organism's tissues, and the level can be much higher as compared with that of the surrounding environment.

A general marine food web is found to be affected by MP contamination in all five trophic levels. MP bioaccumulation seems to be more closely associated with feeding strategies than with the trophic levels of marine species. MPs may undergo biomagnification due to their non-degradable nature when ingested by fish and other aquatic organisms (Reisser *et al.*, 2014). In addition to containing harmful additives, MPs can absorb toxic chemicals (Wang *et al.*, 2018; Wang and Wang, 2018) and harbour microbes from surrounding seawater. These contaminants are transferred into fish through the food chain, posing a significant threat to the fisheries sector (Yoshida *et al.*, 2016). Ultimately, bioaccumulation and biomagnification are essential concepts in EcoRA, providing insight into the extent of pollutant transport within food webs (Miller *et al.*, 2020). Therefore, targeted field-based and experimental studies could be considered to understand the routes of MPs uptake in the food chain (Miller *et al.*, 2023).

Assessing the ecological risks associated with MP pollution is critical for understanding its impact on various environments. In this context, methods such as pollution load index (PLI) and pollution hazard index (PHI) have been used to study different regions for the EcoRA of MP pollution level and to analyse the polymer

toxicity. The PLI helps categorise regions based on their pollution levels, indicating whether they fall under low, moderate, or high-risk categories. For instance, studies have shown that areas with high PLI scores are often associated with significant ecological risks due to elevated concentrations of MPs (Doan *et al.*, 2023; Tajwar *et al.*, 2023). The PHI serves as a critical tool for prioritising management strategies and regulatory measures aimed at mitigating MP pollution. By highlighting the most hazardous MP polymers based on their toxicity and environmental impact, it guides policymakers in focusing efforts on reducing exposure to these materials (Li *et al.*, 2023; Yuan *et al.*, 2022a). In addition to this, various other methods and indices have been employed and used that help assess contamination levels, potential hazards, and the overall impact of MPs on ecosystems. Potential ecological risk index evaluates the ecological risks posed by MPs based on their concentrations and associated toxicity to provide a comprehensive risk assessment (Amrutha *et al.*, 2022). The Hkanson technique is another method utilised for assessing ecological risks related to MPs, which allows for a detailed hazard analysis in specific environments (Rakib *et al.*, 2022; Tajwar *et al.*, 2023). In addition to this, researchers also focus on spatial characterisation and bio-toxicity assessments to understand how MPs distribute in different environments and their effects on local biota. Studies often involve mapping MP concentrations across various habitats (e.g. rivers, lakes, and coastal areas) to identify hotspots of contamination (Qiu *et al.*, 2023). Nevertheless, there is no framework to evaluate the ecological risks of MPs in different environmental media on a national scale under the aspects of spatial characterisation and bio-toxicity as well as anthropogenic impacts (Qiu *et al.*, 2023).

Effect of microplastics on the organisms

Effect on the primary producers

The impact of MPs on different components of the food chain has been investigated, with studies revealing that MPs can negatively impact soil fauna and stimulate microbial activity, leading to potential consequences on soil carbon and nutrient cycling (Lin *et al.*, 2020). The ingestion of MPs by fish, birds, turtles, and marine mammals can lead to various negative impacts, such as digestive system blockages, malnutrition, reduced reproductive success, and impaired immune function (Blackburn and Green, 2022). MPs can also act as carriers for toxic chemicals, such as pollutants and pesticides, which can accumulate in the tissues of organisms. Furthermore, MPs can cause physical damage to organisms, such as tissue inflammation, lesions, and organ damage (Fournier *et al.*, 2021). The presence of these omnipresent MP polymers has been located in compost, which therefore makes a route towards agricultural fields (Weithmann *et al.*, 2018; Yang *et al.*, 2021). Consequently, the negative impact on seed germination and overall growth of the plant, reduced photosynthesis due to reduced chlorophyll count in the plant cells, and lower mineral and nutrient uptake from the root hair have been recorded (Jia *et al.*, 2023). Table 1 highlights divergent kinds of polymers producing diverse negative impacts on plant health and growth. A recent study investigated the toxicological effects of PS-MPs, cadmium (Cd), and

their combined contamination on the growth and physiological responses of *Vicia faba* seedlings (Wang *et al.*, 2024). The results revealed an interference in nutrient transport within the plant, leading to oxidative damage. Furthermore, the presence of PS-MPs was observed to be responsible for reduced seed germination of three ornamental plants, thereby reducing the germinating index (Guo *et al.*, 2022). In addition, the sources, uptake, trophic transfer, translocation, and biological effects of MPs in terrestrial biota across various trophic levels have been reviewed, highlighting their significant contribution to human toxicity (Rose *et al.*, 2023). Moreover, the potential transfer of MPs from aquatic ecosystems to terrestrial environments, particularly soils, has been emphasised. Soils are identified as primary recipients of MP pollution, which can later be transported back into aquatic ecosystems (Nizzetto *et al.*, 2022).

Effect on the heterotrophic consumers

Several practices, such as dumping waste, leaching, and so on, lead to the travelling of MPs by way of water sources such as streams, rivers, and drains, contributing to their environmental dispersion. These MPs from topsoil make their way into the aquatic ecosystem and accumulate/deposit on the seabed. According to a study, the Abyssopelagic zone (a layer located 4000–6000 Mt below the ocean's surface) was found to have these MP particles, which included some common polymers such as the poly(propylene-ethylene) copolymer and polyethylene terephthalate (Zhang *et al.*, 2020). Although some of the polymers settle down on the surface, while the rest float freely under the influence of currents into the ocean and are often mistaken for food by sea fauna (Onyango, 2020)

Organisms across all levels of the marine food chain have been found to ingest MPs, with lower trophic level organisms, such as zooplankton and invertebrates, being particularly vulnerable to their harmful effects (Ivar Do Sul and Costa, 2014). MP ingestion can cause mechanical impacts, such as blocking feeding appendages and the alimentary canal, ultimately reducing the rate of food intake (Cole *et al.*, 2013). For instance, species such as *Centropages typicus* have been observed to consume MPs, resulting in physical retention of these particles in their digestive systems (Chatterjee and Sharma, 2019). Exposure of marine organisms to MPs has been revealed to have increased mortality rates, lowered respiration rates, inhibited the larval growth stage of the life cycle, decreased fertility, and led to starvation in several other organisms (Rubio *et al.*, 2020; Wu *et al.*, 2022). As primary consumers experience decreased health and reproductive rates, the populations of higher trophic levels (e.g. fish) that rely on these organisms for food may also decline (Chatterjee and Sharma, 2019). This disruption can alter predator–prey dynamics and affect overall biodiversity within aquatic ecosystems. In addition, studies indicate that ingested MPs can be absorbed by intestinal epithelial cells and translocate into the circulatory system (Cocci *et al.*, 2022; Jin *et al.*, 2019).

Table 1 summarises how lodging of various types of MPs in organisms has lethal effects, such as organ dysfunctionality and

Table 1. The table illustrates the occurrence of microplastics within the terrestrial ecosystem and across different trophic levels

Present in	Polymer type	MP type	Effects	References
Soil	PE, PP, pVC, pET, PS, pMMA, LDPE	Fibre, fragment, film, microbead, pallet, foam, and bulk	Soil degradation, ecotoxicity, groundwater contamination, soil porosity, reduced fertility, rise in soil pH, reduced soil fauna, and reduction in water holding capacity	Beriot <i>et al.</i> (2021), Li <i>et al.</i> (2023), Piehl <i>et al.</i> (2018), and Wang <i>et al.</i> (2023)
Primary producers	—	—	—	—
(a) Plants	PS, PP, PE, PVC, PE + PVC	Micro beads	Inhibit seed germination, reduce absorption of water and nutrients, reduce plant growth, and absorb on the root surface	Khan <i>et al.</i> (2024)
<i>Triticum aestivum</i> , <i>Lactuca sativa</i> , <i>Zea mays</i> , <i>Lepidium sativum</i>	PS, PMMA, PE, PLA	Micro beads (labelled with Nile blue)	Bioaccumulation in roots, stems, and leaf cells, distribution among plant cells, and reduced germination rate	Jia <i>et al.</i> (2023) and Li <i>et al.</i> (2020)
(b) Phytoplankton	PE, PS, Nylon, Fibres	Micro beads and micro fibres	Effects on chlorophyll content, growth, ingestion, photosynthesis activity, structural changes, survival, and physical effects	Rodrigues <i>et al.</i> (2021)
<i>A. variabilis</i>	HDPE	—	Reduced growth in high concentrations of MPs	Gopalakrishnan <i>et al.</i> (2023)
<i>P. tricornutum</i> <i>C. gracilis Thalassiosira sp.</i>	PVC	—	Reduced chlorophyll content, reduced photosynthesis, and absorption cause physical damage to the cells	Wang <i>et al.</i> (2020)
Primary consumers	—	—	—	—
(a) Zooplankton	PVC, nylon, ethylene-vinyl acetate, PUR	Microfibres, fragments, and micro pallets	Ingestion of particles and bioaccumulation	Goswami <i>et al.</i> (2020)
For example, <i>Sagittioidea</i> and <i>Copepoda</i>				
(b) Fish	PE, PS, PUR, nylon, microfibres	Microfibres, fragments, micro pallets, bulk, and microbeads	Causes inflammation, changes in swimming behaviors, respiratory effects, oxidative stress, reproductive effects, and bioaccumulation	Assas <i>et al.</i> (2020), Goswami <i>et al.</i> (2020), and Kim <i>et al.</i> (2021)
For example, <i>Alepes djedaba</i> , <i>Saurida tumbil</i> , <i>Gerres filamentous</i> , <i>Nemipterus peronei</i> , <i>Carangoides malabaricus</i> , and so on				
(c) Cow	PE, PS	Microfibres and micro-fragments	Accumulation of toxic compounds in gut tissues, impaired fertility, and enter the blood circulation	Grechi <i>et al.</i> (2023) and Sheehan <i>et al.</i> (2022)
Secondary consumers	—	—	—	—
(a) Humans	PP, PS, PET, PMMA	Microfragments, microfibres, microfilm, and microparticles	Reaches placenta tissues at all levels, transportation by bloodstream, bioaccumulation in internal organs (lungs, kidneys, liver, etc.), particle toxicity, oxidative stress, inflammatory lesions, impaired immune response, chronic inflammation, neoplasia risk, and so on	Jiang <i>et al.</i> (2024), Prata <i>et al.</i> (2020), and Ragusa <i>et al.</i> (2021)

blockage due to accumulation, as in case of tissues, muscles, and gills. MPs can bioaccumulate in the tissues of heterotrophic consumers, leading to biomagnification through the food web. As larger predators consume smaller organisms contaminated with MPs, they may accumulate higher concentrations of both MPs and associated toxic substances (e.g. heavy metals and persistent organic pollutants) that adhere to plastic surfaces (Miller *et al.*, 2020). This process raises concerns about the long-term health effects on apex predators, including humans who consume seafood.

The latest studies delve into the potential risks associated with the exposure of MPs to the human body through inhalation, ingestion,

and skin contact (Alqahtani *et al.*, 2023; Sun and Wang, 2023). Supported by scientific evidence, it elucidates the capacity of these materials to infiltrate systemic circulation, accumulate in diverse organs, and exert multi-faceted impacts on development, growth, reproduction, behaviour, and mortality across aquatic and terrestrial animals (Cox *et al.*, 2019; Parenti, 2021).

Effects of MPs on gastrointestinal system

The gastrointestinal (GI) effects of MPs are a growing area of concern and research, as the ingested MPs can accumulate and cause physical blockages or irritation in the digestive tract. This can lead to symptoms such as abdominal pain, altered bowel habits, and in severe cases, GI tract obstruction (Fournier *et al.*, 2021, 2022;

Turroni *et al.*, 2021). However, the retention time and potential accumulation in the GI tract may vary depending on the size, shape, and type of MPs. The interaction of MPs with the immune cells in the GI tract may lead to an overactive immune response or immune suppression, both of which can have detrimental effects on gut health and overall immunity (Di Sabatino *et al.*, 2015). The ability of MPs to accumulate heavy metals from the environment and transfer them to the digestive system of organisms through the food chain has been studied recently (Jiang *et al.*, 2024). The results revealed that biodegradable MPs, particularly polylactic acid (PLA), could pose more health risks by accumulating and transferring heavy metals such as Cd during human digestion as compared with that of conventional MPs (i.e. PP and polyamide) (Jiang *et al.*, 2024).

The GI effects of MPs are complex and multi-faceted, involving physical, chemical, microbiological, and immunological interactions. While significant progress has been made in understanding these effects, ongoing research is essential to elucidate the full impact on human health and to develop strategies to mitigate exposure and potential risks (Jones *et al.*, 2023; Visalli *et al.*, 2021).

Effects of MPs on neurological system

MPs have also been associated as a leading cause of the rise of neurological disorders, affecting brain functionality to a greater extent. Research studies revealed the role of MPs and associated mechanisms of how these polymers hinder brain activity by DNA damage and cause changes in gene expression, stress response, and inflammatory response (Abdel Hamid *et al.*, 2020; Niaz *et al.*, 2020; Salem *et al.*, 2020). The heightened risk of neurodevelopmental toxicity due to interference of MPs/NPs in breaching blood–brain barrier and inducing detrimental effects, namely, oxidative stress, cellular stress, DNA damage, alterations in inflammatory response, and apoptosis within the central nervous system, has been documented (Martin-Folgar *et al.*, 2024). Another study suggested size-dependent toxicity of MPs/NPs and revealed that PS MPs/NPs significantly elevated the expression of *gst-4*, which encodes glutathione *S*-transferase-4, a key enzyme in oxidative stress (Lei *et al.*, 2018). In laboratory studies, MPs have been observed to inhibit acetylcholinesterase activity, an enzyme crucial for neurotransmission, potentially leading to behavioural changes and cognitive impairments (Prüst *et al.*, 2020).

Researchers studied the impact of MPs on olfactory-mediated behavioural responses of goldfish and observed potential disruption by interfering with odorant recognition, action potential generation, olfactory neural signal transmission, and the processing of olfactory information (Shi *et al.*, 2021). Another study provided evidence of the presence of MPs in the human olfactory bulb, suggesting a potential pathway for their translocation to the brain (Amato-Lourenço *et al.*, 2021). Furthermore, the decreased levels of glial fibrillary acidic protein, associated with early stages of neurodegeneration, have been observed in animal models exposed to MPs, suggesting a potential link to Alzheimer's disease

mechanisms (Prüst *et al.*, 2020; Wang *et al.*, 2024). The chronic inflammation triggered by MP exposure can disrupt normal neuronal function and contribute to the neurodegenerative processes characteristic of Parkinson's disease (Shapiro and Katchur, 2023). Research involving zebrafish models has indicated that MPs can interact with neurotoxins and increase oxidative stress, which may contribute to neurodevelopmental issues, namely, autism spectrum disorders (Savuca *et al.*, 2024).

Effects of MPs on cardiovascular system

The role of MPs in the rise of cardiovascular disorders has been widely studied, and the emerging health concerns have been documented through multiple mechanisms. Liang *et al.* (2024) demonstrated that exposure to MPs/NPs is linked to various cardiovascular ailments such as thrombogenesis, vascular damage, and cardiac impairments. Recent studies have detected MPs in atherosclerotic plaques, particularly in carotid arteries. In a multi-centre observational study involving patients undergoing carotid endarterectomy, it was found that 58% of the patients had MPs, primarily polyethylene and PVC, in their carotid plaques. The presence of these particles was associated with a significantly higher risk of major cardiovascular events, including myocardial infarction and stroke. Specifically, patients with MPs in their plaques had a higher risk of experiencing serious cardiovascular outcomes compared with those without detectable MPs (Huynh, 2024; Marfella *et al.*, 2024). MPs can promote cell senescence and disrupt normal endothelial function. Endothelial cells lining blood vessels are crucial for maintaining vascular health, and their dysfunction is a precursor to various cardiovascular diseases (Prattichizzo *et al.*, 2024; Zheng *et al.*, 2024). Oxidative stress is a critical factor in endothelial dysfunction, which can impair vasodilation and promote atherosclerosis, a major contributor to cardiovascular disease (Olatunji *et al.*, 2024; Zheng *et al.*, 2024). When combined with other environmental pollutants, such as heavy metals or endocrine disruptors, the cardiotoxic effects of MPs may be exacerbated, leading to greater risks for cardiovascular health (Prattichizzo *et al.*, 2024; Zheng *et al.*, 2024). MPs can elicit an inflammatory response by interacting with immune cells, such as macrophages, which may lead to the upregulation of pro-inflammatory cytokines, perpetuating a state of inflammation that contributes to cardiovascular pathology (Persiani *et al.*, 2023).

Effects of MPs on respiratory system

The heterogeneous characteristics of MPs as contaminants in the respiratory system, following inhalation, raise concerns about potential deleterious health outcomes. Evidence indicates the widespread presence of airborne microplastics (AMPs) globally, sparking concerns for human health, like deposition in the respiratory tract, translocation, and in vitro/in vivo toxic effects (Amato-Lourenço *et al.*, 2021; Dzierżyński *et al.*, 2024; Goodman *et al.*, 2021). The physical characteristics of AMPs influence cellular interactions, manifesting in cell membrane damage and oxidative stress, and prolonged exposure to AMP-associated toxicants raises significant health concerns (Vattanasit *et al.*, 2023). Exposure to

MPs stimulates lung epithelial cells to produce pro-inflammatory cytokines such as TNF- α , IL-6, and IL-1 β . This inflammatory response can lead to chronic lung conditions and exacerbate existing respiratory diseases, such as asthma and chronic obstructive pulmonary disease (Abad López *et al.*, 2023; Baeza-Martínez *et al.*, 2022; Lu *et al.*, 2022). MPs can increase reactive oxygen species levels in lung cells, leading to oxidative damage. This oxidative stress is a critical factor in the pathogenesis of various lung diseases, including acute respiratory distress syndrome (Lu *et al.*, 2022; Vasse and Melgert, 2024).

A retrospective case series, involving 22 participants with respiratory conditions, utilised the sputum samples to investigate the presence of MPs, and results indicated the unintended inhalation of MPs from diverse sources (Huang *et al.*, 2022). In another study, the presence of MPs majorly PP and polyethylene, in human lung tissues obtained at autopsies was confirmed, which might play a prominent role in detrimental health outcomes (Amato-Lourenço *et al.*, 2021). Currently, it is too early to draw definitive conclusions about the potential effects of AMP levels on lung health. Specifically, more investigation is needed into the effects of AMPs on respiratory tract cells and the underlying mechanisms of cell damage.

Effects of MPs on reproductive system

MP contamination poses a significant threat to the reproductive health of aquatic species, potentially resulting in far-reaching ecological consequences. Experimental evidence shows that MPs can accumulate in the testes and ovaries, leading to inflammation and oxidative damage in these glands and germ cells (Marcelino *et al.*, 2022). Liu *et al.* (2022) reported the accumulation of MPs in the intestines, ovaries, and uterus of exposed mice. Similarly, a study on BALB/c female mice revealed that MPs not only damage the uterus but also impair immune function within the reproductive system, posing challenges for animal breeding (Hu *et al.*, 2021). The impact of PS-MPs on zebrafish was recorded, and a significant alteration in fish gonads revealed the adverse impact of MPs on fish reproductive organs (Qiang and Cheng, 2021).

Notably, exposure of MPs to marine species has been correlated with reproductive toxicity, manifesting in compromised gamete quality, reproductive success, and diminished offspring viability (Bhat *et al.*, 2024; Hasan *et al.*, 2024; Hong *et al.*, 2023; Liang *et al.*, 2024). The harmful nature of these risks is highlighted by the transfer and accumulation of MPs/NPs in various organs during larval stages (Kaur *et al.*, 2024; Liang *et al.*, 2024). A significant contribution of MPs in a widespread decline in fertility of animals and humans was studied using *in vitro* and *in vivo* experimental findings (Grechi *et al.*, 2023). In a study, the presence of MPs was detected in placental parts, namely, maternal, foetal, and amniochorial membranes, which is alarming as this may trigger an immune response and be harmful for pregnancy (Ragusa *et al.*, 2021). Also, an alteration in several cellular regulating pathways, namely, immunity mechanisms and growth-factor signalling

during pregnancy due to interference of MPs, has been studied earlier (Ilekis *et al.*, 2016). The damaging effect of PVC-MPs on the reproductive and digestive systems of both male and female mice was studied, with pronounced sex-dependent effects on intestinal microflora composition. These changes in microflora are closely associated with PVC's impact on reproductive organs (Yang *et al.*, 2024). As research continues to evolve, it is crucial to understand the full scope of these impacts and develop strategies for mitigating exposure to MPs to protect reproductive health.

Potential challenges in MPs detection: MPs present significant challenges in detection and quantification across various environmental matrices

Size variability

Diverse size ranges of MPs vary widely in size, and the presence of NPs (less than 100 nm) poses an even greater challenge due to their ability to cross-biological barriers more easily and their smaller size, which complicates detection methods (Ivleva, 2021; Yee *et al.*, 2021). Moreover, several conventional detection methods are not optimised for the full range of MP sizes, making it difficult to accurately identify and quantify particles, especially those at the lower end of the size spectrum (Jin *et al.*, 2022; Lamichhane *et al.*, 2023).

Chemical diversity

There are over 20 different types of plastics in use, each with unique chemical properties and degradation patterns. This diversity complicates the identification and quantification processes, requiring sophisticated analytical techniques for accurate assessment (Ivleva, 2021). Also, MPs often contain various additives (e.g. plasticisers and stabilisers) and can adsorb environmental pollutants. These factors can interfere with detection methods and lead to false positives or negatives (Ivleva, 2021; Lv *et al.*, 2021). The mechanisms and extent of plastic dispersion across various environmental components remain critical issues that require further investigation (Yin *et al.*, 2019).

Complex matrices

Environmental samples often contain a mix of organic and inorganic materials, which can make it challenging to isolate MPs. The presence of natural particles may lead to misidentification or difficulty in quantifying MPs accurately (Jin *et al.*, 2022). Moreover, the need for effective sample preparation techniques, such as density separation and digestion of organic matter, is crucial for isolating MPs from complex matrices. However, these processes can introduce variability and complicate the analysis (Lv *et al.*, 2021).

Lack of standardisation

Currently, there is no standardised method for the detection and quantification of MPs across different studies and industries. This lack of standardisation leads to significant variations in reported

concentrations, hindering effective policymaking and treatment strategies (Jin *et al.*, 2022). The absence of consistent methodologies makes it challenging to compare results across different studies or regions, limiting our understanding of the extent and impact of MP pollution globally (Lv *et al.*, 2021).

Strategies to control the interference of microplastics

MPs pose a significant threat to marine ecosystems and the food chain, affecting various organisms from plankton to larger marine mammals. Addressing this issue requires a multi-faceted approach that combines policy interventions, technological advancements, and community involvement. Recent research highlights several strategies to mitigate MP pollution and its impacts.

Policy interventions

Robust policy measures are crucial for controlling MP pollution. Implementing regulations to reduce plastic production and usage, particularly for single-use plastics, can control the MPs pollution. The European Union has already banned primary MPs and is promoting circular economy practices (Amelia *et al.*, 2021; Hrustić, 2022). International and interdisciplinary collaboration and information sharing are essential for advancing research and achieving standardisation and harmonisation of testing methods. In addition, the creation of shared databases can help minimise the time and costs involved in supporting well-informed policy decisions at both national and international levels. Further research is necessary to reduce uncertainties, conduct more comprehensive risk assessments of MP pollution across various environmental media, and guide cost-benefit analyses for different mitigation policy strategies. By initiating a substantive reduction in the manufacturing of plastics through the implementation of regulatory frameworks and incentives for sustainable alternatives, the MP production can be controlled (Kumar *et al.*, 2021).

Wastewater treatment improvements

There is a need to upgrade wastewater treatment facilities to better capture MPs before they enter water bodies. Current systems often fail to retain smaller particles, allowing them to escape into the environment (Hettiarachchi and Meegoda, 2023). Although 90% of MPs have been removed from wastewater during primary, secondary, and tertiary treatments, particles smaller than 250 µm do not get separated during these treatments (Meegoda and Hettiarachchi, 2023). These MPs remain suspended in sewage sludge and re-enter the ecosystem when the sludge is used as biosolids for land applications. Hence, the cycle of entering the MPs into aquatic environment through stormwater runoff continues with the spread of pollution (Golwala *et al.*, 2021). Hence, there is an essential requirement of closure of the MP cycle between landfills and wastewater treatment plants, along with the enforcement of quality control practices on recovery/upcycling associated with plastics. Therefore, by developing advanced filtration technologies for wastewater treatment that can capture smaller MPs effectively

would help in hindering the translocation of MPs into food webs (Castillo-Diaz *et al.*, 2023; Meegoda and Hettiarachchi, 2023).

Microbial degradation

The use of microorganisms and the associated microbial processes that can break down plastics or mitigate their effects in marine environments could help alleviate MP pollution. Microorganisms, including bacteria, fungi, and microalgae, have shown varying abilities to degrade plastics through enzymatic processes. Under aerobic conditions, these microbes utilise oxygen to convert plastic polymers into simpler compounds, such as carbon dioxide and water. Conversely, anaerobic conditions may lead to different degradation pathways. For instance, certain bacteria can produce enzymes that facilitate the hydrolysis of plastics, breaking them down into smaller oligomers or monomers that can be assimilated as a carbon source for microbial growth (Vaksmas *et al.*, 2021; Viel *et al.*, 2023).

Microbes and microbial consortia can degrade complex hydrocarbons, such as petroleum and PAHs, which share chemical similarities with certain polyolefin-type plastics. Consequently, plastic polymers could potentially serve as substrates for microorganisms (Wayman and Niemann, 2021). Similarly, several microbial strains have been researched for their potential in plastic degradation/depolymerisation, namely, multiple strains of *Pseudomonas* sp. (Kyaw *et al.*, 2012; Pramila, 2012), *Bacillus* sp. (Ingavale and Raut, 2018; Syranidou *et al.*, 2017), and *Aspergillus* sp. (Esmaili *et al.*, 2013; Pramila and Ramesh, 2011). However, the role of microbes in plastic degradation in the ocean and associated metabolic pathways is not clearly understood. Nevertheless, certain techniques have been applied for the assessment of polymer biodegradation, such as measuring the gravimetric mass loss of plastics. Furthermore, atomic force microscopy helps in measuring surface changes (quantitative and qualitative) (Ojha *et al.*, 2017); Fourier transform infrared spectroscopy coupled to attenuated total reflectance has been used for polymer identification and evaluation of degradation (Almond *et al.*, 2020).

Environmental management

The effective management of marine ecosystems can help trap and reduce MPs. This can be done by protecting and restoring habitats, such as mangroves, seagrasses, and salt marshes, which can act as natural filters for MPs due to their structural complexity (de los Santos *et al.*, 2021). Researchers have suggested that seagrass meadows and other aquatic canopy-forming ecosystems should be prioritised in assessments of MP exposure and its impact on coastal areas, as they can accumulate high concentrations of MP particles, potentially affecting the associated fauna (Chatterjee and Sharma, 2019). Furthermore, the establishment of comprehensive monitoring programmes to assess MP levels in various marine environments and their biological impacts on marine life could positively impact the environmental balance (Alfaro-Núñez *et al.*, 2021).

Research and development

Ongoing research is vital for understanding the dynamics of MPs in marine environments. The mechanism of how MPs affect different marine organisms, particularly those at the base of the food chain (plankton), could be identified by investigating the scientific evidence. Research indicates that MPs can disrupt nutrient cycling and carbon storage processes essential for ocean health (Asher, 2023). Furthermore, by developing models to predict the long-term effects of MP ingestion on marine food webs and biogeochemical cycles, potential strategies can be implemented for controlling MPs (Asher, 2023; Fältström and Anderberg, 2020). Certain species, particularly carnivorous fish, show high levels of MP ingestion, raising concerns about bioaccumulation and its implications for human health through seafood consumption (Alfaro-Núñez *et al.*, 2021). Investigations into coral reefs revealed that MPs can impair feeding mechanisms and promote harmful bacterial growth, leading to increased mortality rates in affected corals (Corinaldesi *et al.*, 2021). Also, it is crucial to research and promote the use of biodegradable materials that do not contribute to MP pollution (Amelia *et al.*, 2021). By combining these strategies with ongoing research efforts, it is possible to mitigate the interference of MPs in the food chain and protect marine life effectively. Furthermore, by conducting extensive research to elucidate the sources and pathways of MPs in different ecosystems will help in providing the solution to marine pollution.

In addition, researchers have emphasised various strategies to address MP pollution. Utilising advanced polymer characterisation tools can enable faster and more accurate detection of SMPs in water, facilitating timely interventions before they transform into micropollutants. Improved detection and characterisation technologies are crucial for increasing awareness of MP pollution. Efforts should focus on redirecting plastic waste from landfills and the natural environment towards innovative solutions, such as reuse, recycling, and recovery initiatives. In addition, advanced membrane technologies, including micro-, ultra-, and nanofiltration systems, should be explored for the effective removal of SMPs from wastewater treatment plant effluents and seawater (Malankowska *et al.*, 2021).

Integrate remote sensing technologies, satellite imagery, and sensor networks could work well to create a real-time monitoring framework for tracking the movement and concentration of MPs. The recent involvement of artificial intelligence in the removal of MPs has been explored by combining it with technologies such as biofilter technology using hydrogel in spectroscopy and microscopic techniques, and so on, which may help in the detection and mitigation of certain types of MP polymers (Jin *et al.*, 2024).

Conclusion

As the MPs have made their way into every corner of the earth, the glaciers, the deep seas, and organisms as well, it is important to find ways to study the accumulation of MPs at trophic levels. Also, on examining various pathways of exposure, including skin

contact, inhalation, and ingestion, it has become crucial to understand the toxicity associated with MPs. While the literature on human ingestion and exposure is limited, certain reviews have unearthed significant insights into ingestion across trophic levels. The prevalence of discarded plastic, particularly in aquatic environments, raises serious concerns about its potential impact on both animal and human health. The complex journey of MPs within the human body, involving uptake, transportation, distribution, and bioaccumulation, is influenced by diverse factors, including size, shape, type, carried pollutants, physiological states, and other yet undiscovered elements. This complexity underscores the need for a comprehensive investigation into the pharmacokinetics of various types of MPs. Such research should consider the refined interactions of these particles within the human body, recognising the diverse characteristics and individual variations that contribute to their impact on the circulatory and lymphatic systems.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author's contribution

Rashika Parmar: conceptualisation and writing draft; Sheetal Thakur: manuscript preparation and revision; Ajay Singh: data verification and correction; Preeti Rajesh: reviewing and manuscript revision; Arun Kumar Singh: editing and revision; Subhadra Rajpoot: reviewing and plagiarism detection.

Conflict of interest

The authors do not have any conflict of interest.

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