



Review Article

Microplastics: Potent Emerging Contaminants Capable of Disrupting the Biogeochemical Balance of the Biosphere

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The biosphere has been suffering severely from the ill effects of various emerging contaminants. Microplastics are among those that can pose serious threats and elicit widespread consequences. The chemical inertness, high aspect ratio, and extreme stability mark them as one of the potent destroyers of ecological balance in the marine ecosystem. They can affect the lives of organisms at various levels by encroaching on the aquatic food chain and altering the biogeochemistry of the system. Various biogeochemical cycles that maintain the elemental balance and their distribution from one biosystem to another were disrupted by the action of microplastics. The microplastics will migrate from lower trophic levels to higher ones through the food chain and bioaccumulate in higher-grade organisms like human beings. It's ironic to note that the danger generated by human activity finally accumulates in human beings and causes serious, life-threatening diseases. Microplastics were found in most of the human body parts and even in the brain. They are potent enough to derail the biochemical pathways of the human body as well. Better international co-operations, mitigating policies, and strong leadership to implement the same are required to safeguard our ecosystems for future generations.

Introduction

Emerging contaminants (ECs) have become the buzzword recently [1,2]. It implies a host of potent chemical contaminants and bio-agents that have been detected in various strata of the environment as a result of diverse anthropogenic interventions. They include pathogenic micro-organisms, inorganic nano materials, perfluoro- and polyfluoroalkyl substances (PFAS), personal care products, micro and nano plastics, etc. [3]. The term 'microplastics' has become ubiquitous in the common vocabulary very recently [4]. The arrival of plastics for human use also didn't have a very long history. By 1950, coinciding with the Industrial Revolution, plastics emerged as a convenient and cost-effective material for a wide range of applications [5]. The world was astonished by the fascinating attributes of plastics such as flexibility, mechanical properties, thermal stability, corrosion resistance, easy and cost-effective manufacturing routes, etc. Even though polymers were initially considered a symbol of vanity and the elite class, they soon became an omnipresent and affordable alternative to many commodity materials. Generally, when we use certain materials so dearly, we often ignore

their flaws. Like every material, plastics also have their disadvantages, one being their poor biodegradability. Highly stable materials lasting for ages can be useful for certain applications, but not for all. The non-degradable plastics can stay in the environment for longer periods and can cause harm to living and non-living things directly or indirectly.

The excessive use (or abuse) of plastics without recycling the used plastics leads to plastic pollution, one of the severe environmental concerns of the present century. As per recent statistics from the OECD, global plastic usage grows exponentially every year and is expected to reach approximately 1.2 billion tons by 2060 [6]. Sadly, less than 10% of the global plastics are being recycled and the rest goes on to strangle the world in the form of plastic pollution. The exponential usage, low recycling rate, delayed degradability, and inherent resistance to erosion are responsible for the alarming plastic pollution that disfigures the face of mother nature. This man-made garbage ultimately piled up in the marine environment making the majority of marine trash from surface waters to deep seas. Further, it would cause the deprivation of necessary living conditions to many living things, affecting the biodiversity of major ecosystems.

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The environmental conditions and varying climatic shifts mainly low temperatures and ultraviolet radiation, can act on the plastic materials grinding and slicing them into tiny microscopic pieces commonly called microplastics that can be distributed across the globe by air or water currents. The term microplastics implies “tiny fragments of plastics having less than 5 mm of length”. This name was proposed by Richard Thompson, a European marine ecologist in 2004 when his team found such plastic particles on British beaches [7]. In recent times, there has been much debate on the definition of micro and nano plastics and their size ranges. The plastic fragments with sizes ranging from 1 μm to 5 mm are classed under microplastics, whereas those with sizes between 1 nm and 1 μm are considered as nanoplastics [8].

Microplastics are generally organic polymers composed of long carbon chains with hydrogens and occasionally nitrogen, oxygen, and halogens. Their exemplary chemical stability and high surface area made them more dangerous pollutants. Polyolefins like polystyrene (PS), polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), and polyesters like polyethylene terephthalate (PET) are the most common contributors to the global plastic burden (figure 1). In addition to the bare polymeric fragments, microplastics may contain additives or compounding agents such as plasticizers, conductive additives, catalysts, cross-linking agents, etc., used along with them during the industrial preparation for value-added polymer articles. Diethyl hexyl phthalates (DEHPs), bisphenol A (BPA), tetrabromobisphenol A (TBBPA), and polybrominated diphenyl ethers (PBDEs) are some of them. As most of these chemicals are proven toxic agents, their leaching from the microplastics to the environment poses a significant risk. Yearly over 8 million tons of plastic are dumped into our environment which finally lands in the oceans. The amount of plastic wastes in our environment increases drastically due to ineffective management [9].

The pollution created by microplastics has already raised a lot of alarm and presented numerous risks to marine life. These non-biodegradable pollutants can be seen in large proportions in most watery environments across the globe. The major bottlenecks in removing such microplastics are the high molecular weight, hydrophobic nature, and absence of favourable functional groups. The localization of these pollutants mainly depends on their density. Denser polymers like PS, PET, and PVC were usually deposited at the benthic levels, whereas lighter polymers like polyolefins (PE and PP) often float on the water surfaces [10]. The aquatic life faces severe risk from microplastics because of their small size. They may get consumed by small marine organisms and added to their food chains when they are part of marine ecosystems. Further, this pollution in the marine ecosystem has a wide range of impacts on food quality and safety, health, coastal tourism, and climate change. Microplastic contamination is a serious and pervasive environ-

mental problem with considerable challenges. Even though the global think tank has been striving hard to understand its causes, effects, and possible remedies for the last few decades, it seriously requires persistent international cooperation and innovative actions.

Microplastics can be classified as primary microplastics and secondary microplastics based on their origin. Micro-sized plastic particles or beads are commonly used in the cosmetic or personal care industry, industrial manufacturing, textile industry, etc as raw materials or building blocks. They directly mix with the environment via unintentional spills during transportation, manufacture, or are washed off into effluent systems and are considered primary microplastics. They are composed of lipophilic polymers, viz. PE, PP, PS, and other polyolefin particles are capable of adsorbing other organic pollutants from the surrounding environment. The secondary microplastics are generated by the fragmentation or deterioration of large plastic materials by chemical, physical, or biological actions.

Microplastics are widely prevalent in our environment. As per recent studies, they could be found in our atmosphere, in our waters, in our blood, and even in space. This review focuses on giving an overview of the influence of microplastics on the biosphere and the subsequent alteration in the biogeochemistry and human biochemistry. It also sheds light on the mitigation strategies and the influence of microplastics on human beings.

Genesis of Microplastics

The inherent chemical stability of plastics enables them to be in the environment for quite a long time without any change. Knowingly or unknowingly human interventions contribute to a large pile of plastic garbage on the ocean floor every year. Considering the microplastic depositions, the major contributors are fisheries activities, oil exploration, and inland river flows. Various industrial processes that require polymeric raw materials or produce polymeric products or by-products, discharge micro or nano-sized plastic wastes through their effluent lines that finally reach the ocean [11]. Microplastic fibers originated from the synthetic clothing industry, packaging industry, bags, paints, micro pellets of polymeric raw materials from several industries, etc, accidentally or unintentionally spilled into water bodies and washed into the sea by rivers and rains forming a major chunk of microplastic pollution [12]. Torn or broken parts of plastic utensils, like plastic bags, toys, foam, and

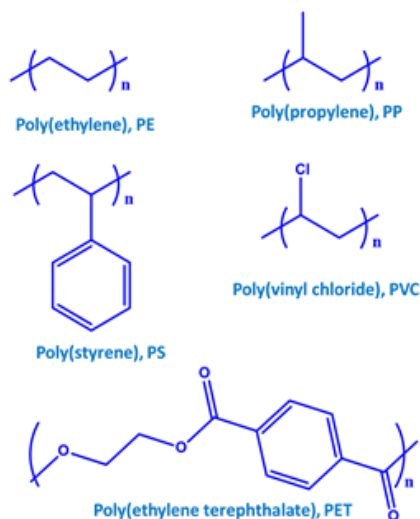


Figure1: Commonly found polymers in plastic garbage



Figure 2: Snapshots from a beach showing the littering of plastic wastes

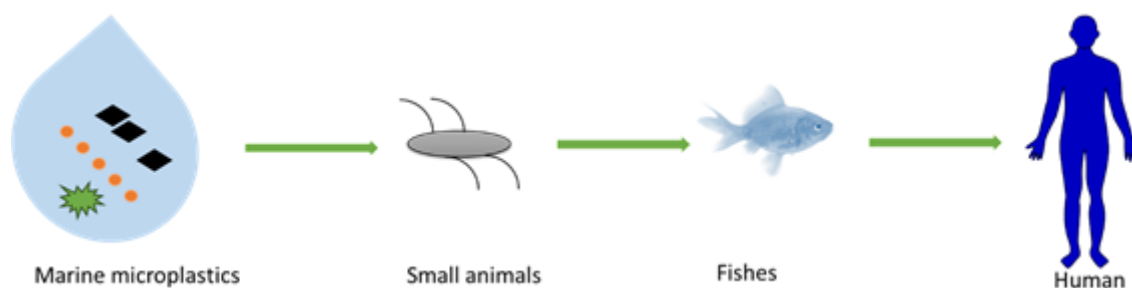


Figure 3: Migration of microplastics from the marine ecosystem to humans via ingestion

fibers on land are carried into the ocean by rivers and wind, resulting in marine plastic pollution. In short, inland flow, wind, and rain are the major contributors of microplastics to the ocean.

Tourism has played another important role in the coastal or marine pollution with plastics. It was noted that the careless approach on the part of tourists throwing plastic bottles, debris, or pouches at the beach or oceans causes a significant load of plastic pollution (figure 2). Also, a huge amount of plastic waste from ships or tourist boats is dumped into the oceans every year. Shipping accidents are also responsible for the arrival of huge amounts of plastic waste in the water bodies. The weathering of these fragments may lead to the creation of microplastics in the aquatic environment. Fishing activities can also contribute to plastic pollution. Fishing nets, ropes, and other gear will wear out due to aging, and interaction with rocks or sharp objects, and end up as microplastics in the marine environment. Moreover, many fishermen abandon old or torn fishing gear and utensils in the sea aggravating the dangers of microplastic pollution. Urban run-off is one of the major sources of microplastics. The pacy lifestyle, the presence of a large number of industrial units, lack of awareness, and lack of proper waste management policies are all responsible for the piling up of plastic waste in the urban run-off. It carries a huge amount of plastic waste that finally ends up in the aquatic environment. Global cooperation and source prevention are mandatory to restrict microplastics in urban run-off [13].

Influence on the Marine Ecosystem

The physical properties of microplastics play a huge role in their distribution. Their transport through the environment is closely related to the mechanical transport connected to water currents and wind flows. Plastic films, for instance, have a larger surface area for atmospheric entrainment than pieces of the same mass because they can differ in thickness and size [14]. The sizes or shapes of microplastics may have a greater effect on living things because smaller, sharper particles can more easily cross membrane barriers than particles with smoother surfaces [15]. The oceans function as the sink where all the plastic garbage carried by terrestrial and freshwater bodies is finally deposited. It further transports the micro- or nano-plastics to the atmosphere via bubble burst ejection and wind-driven sea spray.

The microplastic load of the marine ecosystem increases due to the exponential use of plastic wares as well as the favorable characteristics of plastics, such as resistance to corrosion, durability, non-biodegradability, etc. [16]. Ironically, these are the same characteristics that are responsible for the popularity of plastics. The large surface area to volume ratio and lipophilicity enable the microplastics to anchor other organic pollutants and toxic substances like polycyclic aromatic hydrocarbons (PAHs), petrochemicals from oil leaks, and pesticides from cultivation runoff, etc., prevalent in the marine environment to make them even more hazardous. As they are very small, they are bioavailable for aquatic organisms like fishes, worms, plankton, corals, etc. They enter the marine food chain through small marine organisms by ingestion, bioaccumulate in the food chain, and are transferred to higher trophic levels. Microscopic organisms like copepods are the foundation stones of the marine food chain. Microplastics are reported to harm these organisms. Traboni et al. reported that microplastics can change the feeding habits of *Centropages typicus*, a Mediterranean copepod species

[17]. The destruction of these microorganisms will lead to the starvation and death of their predatory organisms in the upper trophic levels. The global issue of marine plastic pollution has negative local impacts. Microplastics pose a significant threat to marine health, as they are increasingly found in oceans, rivers, and coastal ecosystems. Fishes and marine organisms like turtles consume microplastics, assuming them as their food. Sea turtles are reported to suffer from gastrointestinal blockages and malnutrition after ingesting plastic debris. The growth and reproduction of many filter feeders, like mussels and oysters, were affected due to the tissue accumulation of microplastics. As these small particles move up in the food chain, larger predators like seabirds and marine mammals are also exposed to them and secondary pollutants leaching out of them. The microplastics upset the balance of marine ecosystems and are a real threat to marine biodiversity.

Microplastics in marine environments pose a serious concern because of their potential impact on marine life populations [18]. Microplastic pollutants are extremely harmful to marine organisms and can cause them serious diseases and even kill them. Microplastics were detected in a wide range of marine organisms around the globe, such as crustaceans, turtles, fishes, urchins, birds, etc. [19]. The ingested microplastics can clog the intestinal tract of these organisms, suppress feeding by satiation, inhibit gastric enzyme secretion, cause hormonal imbalance, reproductive disorders, and sterility [20]. The recurring effects of microplastic ingestion cause a significant reduction in the food intake by organisms leading to their death. Biomagnification is another serious threat that originated as a byproduct of microplastic pollution. Toxic contaminants or pesticides like DDT, etc., can be adsorbed onto the surface of microplastics due to their lipophilic nature and this may transfer to the food chain when organisms at the lower trophic levels ingest the microplastics.

Microplastics are believed to have the power to restrict the growth and development of specific organisms in the marine ecosystem. For instance, PS microplastics could inhibit the growth of blow lug lugworm, *Arenicola marina*, and the degree of growth reduction is directly related to the concentration of microplastics to which it is exposed. Similarly, polyethylene microplastics can restrict the feeding and development of the Collector Urchin, *Triploneustes gratilla*. It was reported that exposure to microplastics made some species of algae produce phytotoxins which are harmful to human beings and the environment. These algal toxins are transferred to other organisms like plankton, bivalves or crustaceans via feeding and may transfer to the organisms in the higher trophic levels. One of the common examples of an algal toxin effect due to microplastic exposure is Paralytic shellfish poisoning (PSP). The accumulation of algal toxins in shellfish and subsequent transfer to human beings via ingestion causes hazardous symptoms in humans [21]. The migration of marine microplastics to human beings via various trophic levels is depicted in figure 3.

Corals and coral reefs host extensive biodiversity in the marine ecosystem. Approximately one-third of the total marine fishes and other organisms depend on corals for their habitat and living even though they cover less than 0.5% of the total oceanic area [22]. They meet their energy requirements by the photosynthetic symbiotic algae living on them along with other species like amphipods, copepods, phytoplankton, zooplankton, and other small organisms. If these organisms are contaminated with microplastics, they will finally reach the corals, the

abode of one-third of marine organisms. As the corals cannot digest these non-biodegradable microplastics, they will accumulate in the coral digestive system deteriorating the health of the corals [23]. The most affected part of the coral digestive system due to the ingestion of microplastics is the mesentery tissue within the coral gut cavity, which severely affects coral health [24]. The ingestion of microplastics by phytoplankton derails their capability to photosynthesize energy materials as they penetrate planktonic cell walls and reduce chlorophyll concentrations [25]. Since these organisms play key roles in the marine food chain, any change in their well-being will affect the overall balance of the marine biodiversity and food chains. Furthermore, the accumulated microplastics pass from lower to upper trophic levels through the food chain which ultimately hampers the healthy marine ecosystem.

Influence on Biogeochemistry

The perpetual exchange and conversion of matter and energy between the biosphere and the other active reservoirs of our planet form the biogeochemical cycles. As the biogeochemical cycle unfolds, some molecular species are constantly exchanged and transformed from one form to another via chemical reactions. Microplastic contamination deteriorates the physicochemical, and microbiological features of the soil and ruins the biogeochemical processes of major elements like carbon and nitrogen. Microplastics affect the growth of microbiota responsible for elemental fixation and alter their gene expression to derail their natural cycling. As a result, the natural forms in which the element is to be fixed or emitted are altered haphazardly. This would not only affect the natural fixation of nitrogen or carbon but also affect the entire plant kingdom.

The majority of plastic debris in the marine environment concentrates in the upper strata of the water column, where most of the biogeochemical processes related to marine food chains and value-added resources thrive. Recent studies point out that the presence of microplastics can adversely affect marine biogeochemistry by altering nutrient levels, carbon levels, etc. [26]. It was reported that around 4.8 to 12 million Metric Tons (MT) of plastic land on oceans every year due to human mismanagement [27]. Even though, most of the plastic contaminants are lightweight they are seldom retained on the surface water as the attack of the harsh marine environment alters the size and shape of the plastic wastes. In surface waters, plastic obviously does not have a longer residence duration. Whenever the plastic wastes enter the marine environment, their properties, size, and shape begin to alter with time owing to mechanical fragmentation, embrittlement, and fouling as a result of weathering, and/or biological activity leading them to sink. Hence it would be difficult to estimate the global microplastic content in the ocean basin accurately [28,29].

The dynamic nature of our mother earth is heavily indebted to the smooth running of the biogeochemical cycles. Two of the critical components in terrestrial soil ecosystems are carbon and nitrogen. The emission of greenhouse gases and the bioavailability of nitrogenous and carbonaceous nutrients can be directly influenced by the tweaking of the soil's carbon and nitrogen cycling [30]. Various microorganisms inhabiting the atmosphere, hydrosphere, and geosphere are responsible for the unhindered transformations of the major components of these cycles [31]. These microorganisms are highly susceptible to microplastic pollution and any deviation from their natural physiological function can impact the biogeochemical cycling of critical components. Microplastics will influence the growth and development of plants significantly. By doing so they are indirectly hindering the absorption of nitrogen fertilizers which is a part of nitrogen cycling. This would also affect the CO₂ assimilation by plants, again part of the carbon cycle [32]. The influence of microplastics on soil structure, their effect on water and mineral uptake, and direct toxicity would also cause an imbalance in plant development [33].

Ren et al. reported the influence of microplastics on dissolved organic carbon, greenhouse gas emissions, and the development of bacterial and fungal colonies in the soil environment [34]. The presence of microplastics influences the growth and development of various nitrogen-fixing microorganisms in the soil and thereby derails the normal

nitrogen cycling and affects the concentration of N₂O, a potent greenhouse gas. It is also reported to influence the uptake of methane, another potent greenhouse gas. The effect of polyethylene (PE) microplastics on methane emissions and soil carbon levels was also studied recently. Microplastics are reported to affect methane emissions by regulating the ammonium substrates and methanogens in the soil [35].

Microplastics are capable of transmitting through the food chain of various spheres. Also, they could adsorb or anchor various organic pollutants on their surface due to their high aspect ratio and presence of chemical functionalities. The encroachment of microplastics into the living spheres will affect the natural living of favourable microorganisms that support biogeochemical cycles. Some recent reports highlight that the microplastic contamination of soil causes irrecoverable damage to the soil microorganisms which play a critical role in Nitrogen cycling. According to the next-generation sequencing approach, it was reported that exposure to low-density poly(ethylene)(LDPE) microplastic influenced the network complexity and modularity of the soil bacterial community and limited the abundance of specific genes required for nitrogen cycling [36].

The microbial population is mostly affected by the imbalance that MPs create in biogeochemical cycles. Microplastics can change soils and undersea sediments by changing substrate properties, which leads to biological succession or replacement, as well as transporting invasive species to different habitats or affecting the health of the microbiota through the bioavailability of contaminants. The presence of microplastics in the marine environment has a greater influence on the biogeochemical cycles prevalent in the aquatic ecosystem (figure 4). A recent study pointed out that microplastics like polyurethane form and polylactic acid tend to promote nitrification and denitrification in the marsh sediments whereas PVC microplastics inhibit both processes. This could be due to the functioning of microplastics as organic substrates for the microbial communities [37].

Biological Carbon Pump (BCP) is the term used to represent the cycle of operation by which atmospheric carbon is fixed by photosynthesis by phytoplankton followed by their export and sequestration to the deep ocean. BCP helped significantly to maintain the global CO₂ levels and climatic regulation to the present state [38]. The organic character of microplastics would enable them to function as substrates for the attachment of bacteria and phytoplankton as well. The presence of microplastics is reported to cause a detrimental effect on the chlorophyll content of the phytoplankton which negatively impacts carbon cycling.[39] Microplastics can also affect the cell growth of both phyto- and zooplankton when enter their body via ingestion. The bioaccumulation and biomagnification in plankton impair their physiological functions and natural behaviours severely affecting the marine biological pump. Zooplankton also contributes a major role to carbon fixation by ingesting lower organisms, respiration, and producing faecal pellets and carcasses [40]. They also support the transport of carbon below the thermocline level during their daily migration and seasonal descent [41]. The microplastic contamination of faecal pellets of zooplankton would reduce their carbon-sinking capability and hinder carbon cycling. The attachment and colony formation of phytoplankton over microplastics generate hetero-aggregates which can impact the carbon cycling through the sequestration of particulate organic carbon [42].

A recent report suggested that the introduction of microplastics can affect the dissolved oxygen levels of the marine ecosystem as well. Already the dissolved oxygen level is threatened by global warming. Kvale et al reported that the microplastic ingestion by zooplankton will accelerate global deoxygenation depleting the dissolved oxygen levels [43]. As zooplankton ingest microplastics as food, more amount of organic particles are generated in the nutrient-replete regions aggravating the consumption of dissolved oxygen. Microplastics could impair the growth of microalgae, which have a significant role in the oxygen and carbon cycling in the marine environment [44].

The surface of the plastic forms a new biological niche commonly called the Plastisphere [45]. The surface of microplastics can host many microorganisms. The characteristics of microplastics hosting plastisphere such as cellular uptake, biota tastiness, buoyancy, and interparticle interaction potential of plastic are mainly governed by the nature and chemi-

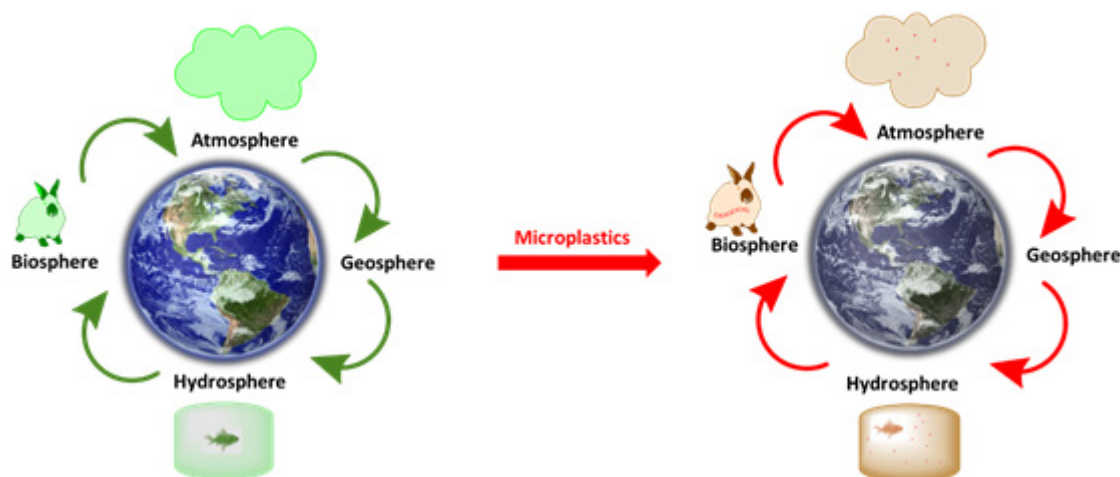


Figure 4: Influence of microplastics on biogeochemical pathways

cal identity of the polymer, its dimension and morphology, and degradation state. These are also the threshold factors controlling their interaction with biogeochemical pathways [46]. The microbiota in the Plastisphere plays a critical role in the downward transport of microplastics, food web uptake, and their degradation in the orifices of soil, and sediment [47]. Recent studies have shown that the mineral, metal, and salt components of the Plastisphere also affect plastic transport in aquatic systems [48]. Even though bulk plastic is a poor conductor of electricity, microplastics may have redox-active surface functional groups formed by weathering. These groups may draw microorganisms that use them as donors or sinks of electrons during their metabolism. This would intensify the electron transfer processes to alter the Organic C pathways, making microbial metabolism more energy efficient. This could lead to reduced methane emissions and quicker decomposition.

Thus, the microplastic pollution adversely affects the marine biota as well as the marine biogeochemistry. The microbial population is the prime victim of the imbalance in biogeochemical cycles caused by microplastics. Microplastics alter the substrate properties of soil or underwater sediments on which these microorganisms grew leading to ecological succession or replacement. Moreover, the transfer of habitat and the bioavailability of organic pollutants affect the health of microbiota [49].

Influence on Human Life and Biochemistry

Like all other organisms, human beings are also facing the challenges of microplastic pollution [50]. For the past couple of decades, the world has been ardently looking at the effect of microplastics on human health and the surrounding ecosystem. Over the past few years, many reports have detected the presence of microplastics in many human specimens, including faeces, blood, and tissues. Yan et al. identified nearly 15 different kinds of Microplastics in human faeces and correlated their effect with inflammatory bowel disease [51]. Subsequently, microplastics with a wide size range were discovered in human thrombi, an alarming sign of widespread prevalence. The studies suggested that the main entry points of microplastics to the human body are through food and water [52]. In addition to this, they have been detected in bronchoalveolar lavage fluid samples, suggesting the possibility of inhalatory administration as well [53]. Dermal absorption of microplastics and plastic additives was also reported [54].

Even though many toxicological evaluations are not available, microplastics are known to cause oxidative stress, histological changes, and inflammatory reactions, as per the reports [55], they are capable of generating various reactive oxygen species (ROS), which may lead to severe oxidative stress at the cellular level. This can mutilate the antioxi-

dant defence mechanisms and damage cell organelles, nucleic acids, intracellular proteins, etc. [56]. The enhancement in ROS levels is reported to cause apoptosis and inflammation [57,58]. The invasion of microplastics can also trigger the release of pro-inflammatory cytokines like IL-6 and TNF- α , etc. leading severe inflammation and epithelial damage [59,60].

When microplastics enter the body via ingestion they can affect digestion and can irritate the GI tract inducing a variety of inflammatory symptoms [61]. Entry of secondary pollutants like heavy metals and polycyclic aromatic hydrocarbons adhered to the microplastic surface could worsen the situation further. Nasal or airway administration of microplastics can induce oxidative stress and irritation in the lungs and airways, and induce sneezing, coughing, and shortness of breath. The inflammation and damage could lead to fatigue and light-headedness due to the reduction in blood oxygen levels [62]. A recent study suggests that nanoplastics can cause mitochondrial damage to human respiratory cells [63]. Exposure to high doses of polystyrene microplastics can damage the lung tissues leading to the onset of chronic obstructive pulmonary disease (COPD) [64].

Microplastics are also reported to cause hormonal imbalance, leading to diverse endocrine disorders affecting the metabolic, and reproductive systems [65]. The additives used for improving the properties of polymers like DEHP and BPA are known to have endocrine and reproductive toxicity for a long. These toxins may enter the body along with microplastics and invoke toxic reactions [57]. Shockingly a recent study with Raman spectroscopy revealed the presence of microplastics in the placentas (called as plasticenta) [66]. A very recent report shockingly revealed that microplastics could pass the blood-brain barrier to accumulate in the brain at an alarming rate [67]. Thus, the grave concern about microplastics enlarges with every passing day. Even though many experimental reports are available on the harmful effects of microplastics on human health, a detailed investigation is warranted to estimate the real harm of microplastics to human health.

Process and Technologies for the Removal of Microplastics

After the surge in the awareness of microplastic prevalence, the global scientific community began steps to remove this dreadful pollutant from our environment. Even though many suggestions and formulations were put forward, most of them failed to give comprehensive results. Research on the development of technologies to remove microplastics is still in its nascent form. Furthermore, there are many hurdles to overcome such as the size, and kind of microplastics, the absence of detec-

tion tools, etc. One would imagine that only a handful of conventional polymers might be present in the microplastic garbage. But it's not the actual case. It is a laborious task to identify the polymer and to choose an effective methodology to mitigate it.

Mainly the methods suggested are classified into three viz., physical methods, chemical methods, and biological methods. Physical methods are one of the primitive methods which doesn't alter the chemical or biological characteristics of water or contaminants. Filtration, adsorption, froth flotation, magnetic separation, and other physical techniques are most commonly used to remove microplastics [68]. Microplastics are successfully eliminated from sewage water and other aquatic systems using these methods. Chemical treatment relies on the sequential application of several chemicals to remove microplastics from water [69]. Chemical treatments are frequently necessary when physical and biological approaches are unable to remove microplastics from wastewater. Flocculation, coagulation, photolytic degradation, electrochemical oxidation, ozonation, and sol-gel technology are the types of chemical treatment processes.

The majority of the currently used microplastic removal techniques belong to physical and chemical categories, such as recycling, pyrolysis, and landfilling. Filtration, adsorption, magnetic separation, and density separation are the most commonly used physical methods to remove microplastics. Chemical methods adopted are mainly coagulation, oxidative treatment, pyrolysis, photocatalysis, electrochemical methods, etc. Chemical recycling techniques involving pyrolysis are most commonly used for the removal of plastic waste [70]. In addition to this, a host of biological methods involving microbial degradation, bioreactors, etc. were also reported to remove microplastic contamination.

The breakdown of microplastics is influenced by both biotic and abiotic factors. Microplastics are created by the breakdown of plastic waste. It can still break up further into smaller, nanoscale plastic particles. Plastic undergoes bio-fragmentation and bio-deterioration processes, which release oligomers and monomers, as a result of the combined action of biotic enzymes and abiotic stimuli. The fundamental process involves the sequential breakdown of polymers into smaller particles, oligomers, dimers, and finally monomers. Following this breakdown, microorganisms help with the mineralization processes. Extracellular enzymes like laccases, lignin peroxidases, lipases, and esterases convert microplastics into more hydrophilic and transform them into carbonyl or alcohol residues [71]. Hydrolase enzymes like lipases, esterases, and cutinases also contributed to the microplastic remediation by intensifying the chain breakdown. Even though these enzymes can crack the polymer surface, they are unable to degrade them. The smaller polymer fragments get assimilated into bacterial cytoplasm and eventually yield monomers after cycling through several metabolic pathways. The role of intracellular enzymes in the degradation of microplastics and how the monomers are absorbed still unclear. It was reported that the metabolic intermediates containing carbonyl and hydroxyl groups generated by the fragmentation of microplastics are metabolized by the tricarboxylic acid cycle and α -oxidation pathway. Mineralization after this transforms the plastic waste into simple organic molecules like H_2O , CO_2 , N_2 , and CH_4 [45].

Recently magnetic nanomaterials were utilized for the removal of microplastics from aquatic bodies. In one of the approaches Nano- Fe_3O_4 was utilized to magnetize microplastics and subsequently they were removed from the water using a magnet [72]. Similarly, electrocatalysis using a composite cathode made of TiO_2 /graphite was employed for the degradation of PVC microplastics [73]. Ionic liquids and their derivatives were also found to have an active role in the mitigation of microplastics. In a recent report, a polyoxometalate ionic liquid was adsorbed on the surface of magnetic nanoparticles composed of Fe_2O_3 / SiO_2 core-shell, and this magnetic POM-supported ionic liquid phase was utilized for the removal of MPs from water [74].

The application of biological agents like microalgae in the degradation of microplastics was also tried recently. Moog et al employed a photosynthetic microalga, *Phaeodactylum tricornutum*, as a chassis to generate an enzyme, PETase which can degrade PET and its copolymers [75]. In comparison with the bacterial system which requires a rich and constant source of carbon to thrive, the algal system doesn't require

a specific carbon supply and is capable to adapt with any environment in which microplastics are profound [76]. It seems that algomics, development of novel biodegrading enzymes that can act on microplastics, and genetic engineering could be the effective strategies for realizing microplastic degradation [77].

Obligatory parasites or saprotrophs like *Zalerion maritimum*, *Aspergillus niger*, *Cladosporium*, and *Penicillium simplicissimum* are the main genera linked to the degradation of various polymers, including polyethylene, polypropylene, and polyethylene terephthalate [78–80]. These organisms use microplastics as their only carbon source following their breakdown by extracellular enzymes. They reduce their hydrophobicity and catalyse the formation of various polar linkages like carbonyl, carboxylic, and ester functional groups. Various fungal strains of *Aspergillus*, *Fusarium*, *Cladosporium*, *Penicillium*, and *Pestalotiopsis* genera showed similar degradation of polyurethane [81–83]. Numerous investigations utilizing bacteria to break down microplastics have been carried out. Multiple environments, such as contaminated sediments, wastewater, sludge, compost, municipal landfills, and harsh climates like Antarctic soils, mangroves, marine sediments, and even in the gut of earthworms have been found to harbour bacteria that can break down microplastics [84,85]. Microbes that reside in extremely harsh environments are known to acquire activated enzyme systems to break down microplastics. Bioinformatics is an innovative and potent tool to accelerate the biodegradation of plastic waste, particularly microplastic particles. By identifying the enzymes engaged in a desired metabolic pathway and aiding in the prediction of the biodegradation pathways of hazardous compounds, bioinformatics databases together with computational techniques form an admirable framework for the degradation of plastic [86].

Conclusions

We, the most advanced and learned inhabitants of the planet Earth produce millions of tons of plastic waste every year. As there's only a very minuscule amount of plastic waste generated are gets recycled, the huge lump of it ends up in our oceans, the abode of a large biodiversity. The plastic waste may undergo weathering to yield microplastics which are equally or a little more harmful to the ecosystem. The microplastics slowly choke the marine ecosystem and in turn, affect the marine biota and biogeochemical cycling. It would influence climatic shifts, global warming, the greenhouse effect, etc. The genie released by human beings would come back to choke them also. The global think tank is drawing plans and policies to safeguard our ecosystem from the ill effects of microplastics. Wider global cooperation and unified and workable strategies are very much required to curb microplastic pollution for a safe and sustainable future.

References

1. G.R. Varatharajan, J.C. Ndayishimiye, P. Nyirabuhoro, Emerging Contaminants: A Rising Threat to Urban Water and a Barrier to Achieving SDG-Aligned Planetary Protection, *Water* 17, 2367 (2025). <https://doi.org/10.3390/w17162367>.
2. F. Wang, L. Xiang, K. Sze-Yin Leung et al., Emerging contaminants: A One Health perspective, *The Innovation* 5, 100612 (2024). <https://doi.org/10.1016/j.xinn.2024.100612>.
3. E. Boahen, L. Owusu, S.O. Adjei-Anim, A comprehensive review of emerging environmental contaminants of global concern, *Discov. Environ.* 3, 144 (2025). <https://doi.org/10.1007/s44274-025-00259-x>.
4. J. Martín, J.L. Santos, I. Aparicio, E. Alonso, Microplastics and associated emerging contaminants in the environment: Analysis, sorption mechanisms and effects of co-exposure, *Trends Environ. Anal. Chem.* 35, e00170 (2022). <https://doi.org/10.1016/j.teac.2022.e00170>.
5. J. Stanley, D. Culliton, A.-J. Jovani-Sancho, A.C. Neves, The Journey of Plastics: Historical Development, Environmental Challenges, and the Emergence of Bioplastics for Single-Use Products, *Eng* 6, 17 (2025). <https://doi.org/10.3390/eng6010017>.
6. OECD, Global Plastics Outlook: Policy Scenarios to 2060, OECD, 2022. <https://doi.org/10.1787/aa1edf33-en>.
7. R.C. Thompson, Y. Olsen, R.P. Mitchell, A. Davis, S.J. Rowland, A.W.G. John, D. McGonigle, A.E. Russell, Lost at Sea: Where Is All the Plastic?, *Science*

- 304, 838 (2004). <https://doi.org/10.1126/science.1094559>.
8. J.P.G.L. Frias, R. Nash, Microplastics: Finding a consensus on the definition, *Mar. Pollut. Bull.* 138, 145-147 (2019). <https://doi.org/10.1016/j.marpolbul.2018.11.022>.
9. P.G.C. Nayanathara Thathsarani Pilapitiya, A.S. Ratnayake, The world of plastic waste: A review, *Clean. Mater.* 11, 100220 (2024). <https://doi.org/10.1016/j.clema.2024.100220>.
10. S. Sharma, S. Chatterjee, Microplastic pollution, a threat to marine ecosystem and human health: a short review, *Environ. Sci. Pollut. Res.* 24, 21530-21547 (2017). <https://doi.org/10.1007/s11356-017-9910-8>.
11. Y. Li, Y. Sun, J. Li, R. Tang, Y. Miu, X. Ma, Research on the Influence of Microplastics on Marine Life, *IOP Conf. Ser. Earth Environ. Sci.* 631, 012006 (2021). <https://doi.org/10.1088/1755-1315/631/1/012006>.
12. T. Basumatary, D. Biswas, S. Boro, A.R. Nava, M. Narayan, H. Sarma, Dynamics and Impacts of Microplastics (MPs) and Nanoplastics (NPs) on Ecosystems and Biogeochemical Processes: The Need for Robust Regulatory Frameworks, *ACS Omega* 10, 17051-17069 (2025). <https://doi.org/10.1021/acsomega.5c01175>.
13. C. Wang, D. O'Connor, L. Wang, W.-M. Wu, J. Luo, D. Hou, Microplastics in urban runoff: Global occurrence and fate, *Water Res.* 225, 119129 (2022). <https://doi.org/10.1016/j.watres.2022.119129>.
14. S. Allen, D. Allen, K. Moss, G. Le Roux, V.R. Phoenix, J.E. Sonke, Examination of the ocean as a source for atmospheric microplastics, *PLOS ONE* 15, e0232746 (2020). <https://doi.org/10.1371/journal.pone.0232746>.
15. V. Hidalgo-Ruz, L. Gutow, R.C. Thompson, M. Thiel, Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification, *Environ. Sci. Technol.* 46, 3060-3075 (2012). <https://doi.org/10.1021/es2031505>.
16. H. Bockhorn, A. Hornung, U. Hornung, D. Schwallier, Kinetic study on the thermal degradation of polypropylene and polyethylene, *J. Anal. Appl. Pyrolysis* 48, 93-109 (1999). [https://doi.org/10.1016/S0165-2370\(98\)00131-4](https://doi.org/10.1016/S0165-2370(98)00131-4).
17. C. Traboni, D. Sarno, M. Ribera d'Alcalà, M.G. Mazzocchi, Microplastics in the menu of Mediterranean zooplankton: Insights from the feeding response of the calanoid copepod, *Centropages typicus*, *Mar. Ecol.* 44, e12760 (2023). <https://doi.org/10.1111/maec.12760>.
18. E.M. Tuuri, S.C. Leterme, How plastic debris and associated chemicals impact the marine food web: A review, *Environ. Pollut.* 321, 121156 (2023). <https://doi.org/10.1016/j.envpol.2023.121156>.
19. J.G.B. Derraik, The pollution of the marine environment by plastic debris: a review, *Mar. Pollut. Bull.* 44, 842-852 (2002). [https://doi.org/10.1016/S0025-326X\(02\)00220-5](https://doi.org/10.1016/S0025-326X(02)00220-5).
20. M.Y. Azzarello, E.S. Van Vleet, Marine birds and plastic pollution, *Mar. Ecol. Prog. Ser.* 37 (1987) 295-303.
21. G.J. Teegarden, A.D. Cembella, Grazing of toxic dinoflagellates, *Alexandrium* spp., by adult copepods of coastal Maine: Implications for the fate of paralytic shellfish toxins in marine food webs, *J. Exp. Mar. Biol. Ecol.* 196, 145-176 (1996). [https://doi.org/10.1016/0022-0981\(95\)00128-X](https://doi.org/10.1016/0022-0981(95)00128-X).
22. H.T. Yap, Coral Reef Ecosystems, in: J. Orcutt (Ed.), *Earth Syst. Monit.*, Springer New York, New York, NY, pp 77-106 (2013). https://doi.org/10.1007/978-1-4614-5684-1_5.
23. C. Ferrier-Pages, J. Witting, E. Tambutte, K.P. Sebens, Effect of natural zooplankton feeding on the tissue and skeletal growth of the scleractinian coral *Stylophora pistillata*, *Coral Reefs* 22, 229-240 (2003). <https://doi.org/10.1007/s00338-003-0312-7>.
24. N.M. Hall, K.L.E. Berry, L. Rintoul, M.O. Hoogenboom, Microplastic ingestion by scleractinian corals, *Mar. Biol.* 162, 725-732 (2015). <https://doi.org/10.1007/s00227-015-2619-7>.
25. Inger Lise Nerland Bråte, Claudia Halsband, Ian John Allan, Kevin Victor Thomas, Microplastics in marine environments; Occurrence, distribution and effects, (Report No. 6754). Norsk institutt for vannforskning (NIVA). <https://hdl.handle.net/11250/283879> (2014).
26. L. Galgani, S.A. Loisele, Plastic pollution impacts on marine carbon biogeochemistry, *Environ. Pollut.* 268, 115598 (2021). <https://doi.org/10.1016/j.envpol.2020.115598>.
27. J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narayan, K.L. Law, Plastic waste inputs from land into the ocean, *Science* 347, 768-771 (2015). <https://doi.org/10.1126/science.1260352>.
28. E. Van Sebille, C. Wilcox, L. Lebreton, N. Maximenko, B.D. Hardesty, J.A. Van Franeker, M. Eriksen, D. Siegel, F. Galgani, K.L. Law, A global inventory of small floating plastic debris, *Environ. Res. Lett.* 10, 124006 (2015). <https://doi.org/10.1088/1748-9326/10/12/124006>.
29. L. Lebreton, M. Egger, B. Slat, A global mass budget for positively buoyant macroplastic debris in the ocean, *Sci. Rep.* 9, 12922 (2019). <https://doi.org/10.1038/s41598-019-49413-5>.
30. J.D. Harindintwali, J. Zhou, B. Muhoza, F. Wang, A. Herzberger, X. Yu, Integrated eco-strategies towards sustainable carbon and nitrogen cycling in agriculture, *J. Environ. Manage.* 293, 112856 (2021). <https://doi.org/10.1016/j.jenvman.2021.112856>.
31. C. Gaylarde, J.A. Baptista-Neto, A. Ogawa, M. Kowalski, S. Celikkol-Aydin, I. Beech, Epilithic and endolithic microorganisms and deterioration on stone church facades subject to urban pollution in a sub-tropical climate, *Biofouling* 33, 113-127 (2017). <https://doi.org/10.1080/08927014.2016.1269893>.
32. M.C. Rillig, A. Lehmann, A.A. De Souza Machado, G. Yang, Microplastic effects on plants, *New Phytol.* 223, 1066-1070 (2019). <https://doi.org/10.1111/nph.15794>.
33. A.A. De Souza Machado, C.W. Lau, J. Till, W. Kloas, A. Lehmann, R. Becker, M.C. Rillig, Impacts of Microplastics on the Soil Biophysical Environment, *Environ. Sci. Technol.* 52, 9656-9665 (2018). <https://doi.org/10.1021/acs.est.8b02212>.
34. X. Ren, J. Tang, X. Liu, Q. Liu, Effects of microplastics on greenhouse gas emissions and the microbial community in fertilized soil, *Environ. Pollut.* 256, 113347 (2020). <https://doi.org/10.1016/j.envpol.2019.113347>.
35. Z. Zhang, Z. Yang, H. Yue, M. Xiao, T. Ge, Y. Li, Y. Yu, H. Yao, Discrepant impact of polyethylene microplastics on methane emissions from different paddy soils, *Appl. Soil Ecol.* 181, 104650 (2023). <https://doi.org/10.1016/j.apsoil.2022.104650>.
36. L. Rong, L. Zhao, L. Zhao, Z. Cheng, Y. Yao, C. Yuan, L. Wang, H. Sun, LDPE microplastics affect soil microbial communities and nitrogen cycling, *Sci. Total Environ.* 773, 145640 (2021). <https://doi.org/10.1016/j.scitotenv.2021.145640>.
37. M.E. Seeley, B. Song, R. Passie, R.C. Hale, Microplastics affect sedimentary microbial communities and nitrogen cycling, *Nat. Commun.* 11, 2372 (2020). <https://doi.org/10.1038/s41467-020-16235-3>.
38. P. Parekh, S. Dutkiewicz, M.J. Follows, T. Ito, Atmospheric carbon dioxide in a less dusty world, *Geophys. Res. Lett.* 33, 2005GL025098 (2006). <https://doi.org/10.1029/2005GL025098>.
39. J.N. Hitchcock, Microplastics can alter phytoplankton community composition, *Sci. Total Environ.* 819, 153074 (2022). <https://doi.org/10.1016/j.scitotenv.2022.153074>.
40. D.K. Steinberg, M.R. Landry, Zooplankton and the Ocean Carbon Cycle, *Annu. Rev. Mar. Sci.* 9, 413-444 (2017). <https://doi.org/10.1146/annurev-marine-1010814-015924>.
41. P.W. Boyd, H. Claustre, M. Levy, D.A. Siegel, T. Weber, Multi-faceted particle pumps drive carbon sequestration in the ocean, *Nature* 568, 327-335 (2019). <https://doi.org/10.1038/s41586-019-1098-2>.
42. S. Casabianca, A. Bellingeri, S. Capellacci, A. Sbrana, T. Russo, I. Corsi, A. Penna, Ecological implications beyond the ecotoxicity of plastic debris on marine phytoplankton assemblage structure and functioning, *Environ. Pollut.* 290, 118101 (2021). <https://doi.org/10.1016/j.envpol.2021.118101>.
43. K. Kvale, A.E.F. Prowe, C.-T. Chien, A. Landolfi, A. Oschlies, Zooplankton grazing of microplastic can accelerate global loss of ocean oxygen, *Nat. Commun.* 12, 2358 (2021). <https://doi.org/10.1038/s41467-021-22554-w>.
44. J.C. Prata, J.P. Da Costa, I. Lopes, A.C. Duarte, T. Rocha-Santos, Effects of microplastics on microalgae populations: A critical review, *Sci. Total Environ.* 665 (2019) 400-405. <https://doi.org/10.1016/j.scitotenv.2019.02.132>.
45. E.R. Zettler, T.J. Mincer, L.A. Amaral-Zettler, Life in the "Plastisphere": Microbial Communities on Plastic Marine Debris, *Environ. Sci. Technol.* 47, 7137-7146 (2013). <https://doi.org/10.1021/es401288x>.
46. L.A. Amaral-Zettler, E.R. Zettler, B. Slikas, G.D. Boyd, D.W. Melvin, C.E. Morrall, G. Proskurowski, T.J. Mincer, The biogeography of the Plastisphere: implications for policy, *Front. Ecol. Environ.* 13, 541-546 (2015). <https://doi.org/10.1890/150017>.
47. J. Jacquin, J. Cheng, C. Odobel, C. Pandin, P. Conan, M. Pujol-Pay, V. Barbe, A.-L. Meistertzheim, J.-F. Ghiglione, Microbial Ecotoxicology of Marine Plastic Debris: A Review on Colonization and Biodegradation by the "Plastisphere," *Front. Microbiol.* 10, 865 (2019). <https://doi.org/10.3389/fmicb.2019.00865>.
48. R. Leiser, M. Schumann, T. Dadi, K. Wendt-Potthoff, Burial of microplastics in freshwater sediments facilitated by iron-organic flocs, *Sci. Rep.* 11, 24072 (2021). <https://doi.org/10.1038/s41598-021-02748-4>.
49. C.M. Rochman, Microplastics research—from sink to source, *Science* 360, 28-29 (2018). <https://doi.org/10.1126/science.aar7734>.
50. N.H. Mohamed Nor, M. Kooi, N.J. Diepens, A.A. Koelmans, Lifetime Accumulation of Microplastic in Children and Adults, *Environ. Sci. Technol.* 55, 5084-5096 (2021). <https://doi.org/10.1021/acs.est.0c07384>.
51. Z. Yan, Y. Liu, T. Zhang, F. Zhang, H. Ren, Y. Zhang, Analysis of Microplastics in Human Faeces Reveals a Correlation between Fecal Microplastics and Inflammatory Bowel Disease Status, *Environ. Sci. Technol.* 56, 414-421 (2022). <https://doi.org/10.1021/acs.est.1c03924>.
52. A. Sun, W.-X. Wang, Human Exposure to Microplastics and Its Associated Health Risks, *Environ. Health* 1, 139-149 (2023). <https://doi.org/10.1021/>

- embhealth.3.00053.*
53. I. Uogintė, A. Vailionytė, M. Skapas, D. Bolanos, E. Bagurskienė, V. Gruslys, R. Aldonytė, S. Byėenkeniė, New evidence of the presence of micro- and nanoplastic particles in bronchioalveolar lavage samples of clinical trial subjects, *Heliyon* 9, e19665 (2023). <https://doi.org/10.1016/j.heliyon.2023.e19665>.
 54. O. Akpojevwe Abafe, S. Harrad, M. Abou-Elwafa Abdallah, Assessment of human dermal absorption of flame retardant additives in polyethylene and polypropylene microplastics using 3D human skin equivalent models, *Environ. Int.* 186, 108635 (2024). <https://doi.org/10.1016/j.envint.2024.108635>.
 55. Z. Liu, X. You, Recent progress of microplastic toxicity on human exposure base on *in vitro* and *in vivo* studies, *Sci. Total Environ.* 903, 166766 (2023). <https://doi.org/10.1016/j.scitotenv.2023.166766>.
 56. A. Chinsonso David, A. Kayode Adebisi, A. Adondua Moses, U. Chinkwu Kenneth, Biochemical Effects of Microplastics on Human Health: A Comprehensive Review, *Sci. Int.* 13, 27–34 (2025). <https://doi.org/10.17311/sciintl.2025.27.34>.
 57. C. Campanale, C. Massarelli, I. Savino, V. Locaputo, V.F. Uricchio, A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health, *Int. J. Environ. Res. Public Health* 17, 1212 (2020). <https://doi.org/10.3390/ijerph17041212>.
 58. L. Lu, Z. Wan, T. Luo, Z. Fu, Y. Jin, Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice, *Sci. Total Environ.* 631–632, 449–458 (2018). <https://doi.org/10.1016/j.scitotenv.2018.03.051>.
 59. Y. Deng, Y. Zhang, B. Lemos, H. Ren, Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure, *Sci. Rep.* 7, 46687 (2017). <https://doi.org/10.1038/srep46687>.
 60. S.B. Fournier, J.N. D'Errico, D.S. Adler, S. Kollontzi, M.J. Goedken, L. Fabris, E.J. Yurkow, P.A. Stapleton, Nanopolystyrene translocation and fetal deposition after acute lung exposure during late-stage pregnancy, *Part. Fibre Toxicol.* 17, 55 (2020). <https://doi.org/10.1186/s12989-020-00385-9>.
 61. H. Bouwmeester, P.C.H. Hollman, R.J.B. Peters, Potential Health Impact of Environmentally Released Micro- and Nanoplastics in the Human Food Production Chain: Experiences from Nanotoxicology, *Environ. Sci. Technol.* 49, 8932–8947 (2015). <https://doi.org/10.1021/acs.est.5b01090>.
 62. S.L. Wright, F.J. Kelly, Plastic and Human Health: A Micro Issue?, *Environ. Sci. Technol.* 51, 6634–6647 (2017). <https://doi.org/10.1021/acs.est.7b00423>.
 63. S. Lin, H. Zhang, C. Wang, X.-L. Su, Y. Song, P. Wu, Z. Yang, M.-H. Wong, Z. Cai, C. Zheng, Metabolomics Reveal Nanoplastic-Induced Mitochondrial Damage in Human Liver and Lung Cells, *Environ. Sci. Technol.* 56, 12483–12493 (2022). <https://doi.org/10.1021/acs.est.2c03980>.
 64. C.-D. Dong, C.-W. Chen, Y.-C. Chen, H.-H. Chen, J.-S. Lee, C.-H. Lin, Polystyrene microplastic particles: *In vitro* pulmonary toxicity assessment, *J. Hazard. Mater.* 385, 121575 (2020). <https://doi.org/10.1016/j.jhazmat.2019.121575>.
 65. L.N. Vandenberg, D. Luthi, D. 'Andre Quinerly, Plastic bodies in a plastic world: multi-disciplinary approaches to study endocrine disrupting chemicals, *J. Clean. Prod.* 140, 373–385 (2017). <https://doi.org/10.1016/j.jclepro.2015.01.071>.
 66. A. Ragusa, A. Svelato, C. Santacroce, P. Catalano, V. Notarstefano, O. Carnevali, F. Papa, M.C.A. Rongioletti, F. Baiocco, S. Draghi, E. D'Amore, D. Rinaldo, M. Matta, E. Giorgini, Plastics: First evidence of microplastics in human placenta, *Environ. Int.* 146, 106274 (2021). <https://doi.org/10.1016/j.envint.2020.106274>.
 67. A.J. Nihart, M.A. Garcia, E. El Hayek, R. Liu, M. Olewine, J.D. Kingston, E.F. Castillo, R.R. Gullapalli, T. Howard, B. Bleske, J. Scott, J. Gonzalez-Estrella, J.M. Gross, M. Spilde, N.L. Adolphi, D.F. Gallego, H.S. Jarrell, G. Dvorscak, M.E. Zuluaga-Ruiz, A.B. West, M.J. Campen, Bioaccumulation of microplastics in decedent human brains, *Nat. Med.* 31, 1114–1119 (2025). <https://doi.org/10.1038/s41591-024-03453-1>.
 68. N. Badola, A. Bahuguna, Y. Sasson, J.S. Chauhan, Microplastics removal strategies: A step toward finding the solution, *Front. Environ. Sci. Eng.* 16, 7 (2022). <https://doi.org/10.1007/s11783-021-1441-3>.
 69. M.B. Ahmed, Md.S. Rahman, J. Alom, Md.S. Hasan, M.A.H. Johir, M.I.H. Mondal, D.-Y. Lee, J. Park, J.L. Zhou, M.-H. Yoon, Microplastic particles in the aquatic environment: A systematic review, *Sci. Total Environ.* 775, 145793 (2021). <https://doi.org/10.1016/j.scitotenv.2021.145793>.
 70. T. Thiounn, R.C. Smith, Advances and approaches for chemical recycling of plastic waste, *J. Polym. Sci.* 58, 1347–1364 (2020). <https://doi.org/10.1002/pol.20190261>.
 71. I. Taniguchi, S. Yoshida, K. Hiraga, K. Miyamoto, Y. Kimura, K. Oda, Biodegradation of PET: Current Status and Application Aspects, *ACS Catal.* 9, 4089–4105 (2019). <https://doi.org/10.1021/acscatal.8b05171>.
 72. X. Shi, X. Zhang, W. Gao, Y. Zhang, D. He, Removal of microplastics from water by magnetic nano-Fe₃O₄, *Sci. Total Environ.* 802, 149838 (2022). <https://doi.org/10.1016/j.scitotenv.2021.149838>.
 73. F. Miao, Y. Liu, M. Gao, X. Yu, P. Xiao, M. Wang, S. Wang, X. Wang, Degradation of polyvinyl chloride microplastics via an electro-Fenton-like system with a TiO₂/graphite cathode, *J. Hazard. Mater.* 399, 123023 (2020). <https://doi.org/10.1016/j.jhazmat.2020.123023>.
 74. A. Misra, S. Zambrzycki, G. Kloker, A. Kotyrbra, M.H. Anjass, I. Franco Castillo, S.G. Mitchell, R. Güttel, C. Streb, Water Purification and Microplastics Removal Using Magnetic Polyoxometalate Supported Ionic Liquid Phases (magPOM SILPs), *Angew. Chem. Int. Ed.* 59, 1601–1605 (2020). <https://doi.org/10.1002/anie.201912111>.
 75. D. Moog, J. Schmitt, J. Senger, J. Zarzycki, K.-H. Rexer, U. Linne, T. Erb, U.G. Maier, Using a marine microalga as a chassis for polyethylene terephthalate (PET) degradation, *Microb. Cell Factories* 18, 171 (2019). <https://doi.org/10.1186/s12934-019-1220-z>.
 76. N. Yan, C. Fan, Y. Chen, Z. Hu, The Potential for Microalgae as Bioreactors to Produce Pharmaceuticals, *Int. J. Mol. Sci.* 17, 962 (2016). <https://doi.org/10.3390/ijms17060962>.
 77. H.P. Manzi, R.A.I. Abou-Shanab, B.-H. Jeon, J. Wang, E.-S. Salama, Algae: a frontline photosynthetic organism in the microplastic catastrophe, *Trends Plant Sci.* 27, 1159–1172 (2022). <https://doi.org/10.1016/j.tplants.2022.06.005>.
 78. T.A.D. Oliveira, R. Barbosa, A.B.S. Mesquita, J.H.L. Ferreira, L.H.D. Carvalho, T.S. Alves, Fungal degradation of reprocessed PP/PBAT/thermoplastic starch blends, *J. Mater. Res. Technol.* 9, 2338–2349 (2020). <https://doi.org/10.1016/j.jmrt.2019.12.065>.
 79. A. Paço, K. Duarte, J.P. Da Costa, P.S.M. Santos, R. Pereira, M.E. Pereira, A.C. Freitas, A.C. Duarte, T.A.P. Rocha-Santos, Biodegradation of polyethylene microplastics by the marine fungus *Zalerion maritimum*, *Sci. Total Environ.* 586, 10–15 (2017). <https://doi.org/10.1016/j.scitotenv.2017.02.017>.
 80. A.E. Nasrabadi, B. Ramavandi, Z. Bonyadi, Recent progress in biodegradation of microplastics by *Aspergillus* sp. in aquatic environments, *Colloid Interface Sci. Commun.* 57, 100754 (2023). <https://doi.org/10.1016/j.colcom.2023.100754>.
 81. S. Khan, S. Nadir, Z.U. Shah, A.A. Shah, S.C. Karunaratna, J. Xu, A. Khan, S. Munir, F. Hasan, Biodegradation of polyester polyurethane by *Aspergillus tubingensis*, *Environ. Pollut.* 225, 469–480 (2017). <https://doi.org/10.1016/j.envpol.2017.03.012>.
 82. A. Magnin, E. Pollet, V. Phalip, L. Avėrous, Evaluation of biological degradation of polyurethanes, *Biotechnol. Adv.* 39, 107457 (2020). <https://doi.org/10.1016/j.biotechadv.2019.107457>.
 83. S. Muenmee, W. Chiemchaisri, C. Chiemchaisri, Enhancement of biodegradation of plastic wastes via methane oxidation in semi-aerobic landfill, *Int. Biodeterior. Biodegrad.* 113, 244–255 (2016). <https://doi.org/10.1016/j.ibiod.2016.03.016>.
 84. Ch.T. Mehmood, I.A. Qazi, I. Hashmi, S. Bhargava, S. Deepa, Biodegradation of low density polyethylene (LDPE) modified with dye sensitized titania and starch blend using *Stenotrophomonas pavanii*, *Int. Biodeterior. Biodegrad.* 113, 276–286 (2016). <https://doi.org/10.1016/j.ibiod.2016.01.025>.
 85. A.K. Awasthi, Q. Tan, J. Li, Biotechnological Potential for Microplastic Waste, *Trends Biotechnol.* 38, 1196–1199 (2020). <https://doi.org/10.1016/j.tibtech.2020.03.002>.
 86. I. Ali, T. Ding, C. Peng, I. Naz, H. Sun, J. Li, J. Liu, Micro- and nanoplastics in wastewater treatment plants: Occurrence, removal, fate, impacts and remediation technologies – A critical review, *Chem. Eng. J.* 423, 130205 (2021). <https://doi.org/10.1016/j.cej.2021.130205>.