Microplastic Pollution in Aquatic Environment: Ecotoxicological Effects and Bioremediation Prospects

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Abstract

Microplastic pollution, or commonly known as “White Pollution,” has been drawing great interest as a new omnipresent environmental pollution. Plastic is potentially used in all kinds of industries, and their irresponsible waste disposal is the reason behind both aquatic and terrestrial pollution. The degradation period of plastic is a long-term process and occurs due to solar radiation, thermal oxidation, thermolysis, photo-oxidation, etc. The end result is tiny particles known as “microplastics” (diameter less than 5 mm) and “nanoplastics” (diameter less than 100 nm). MPs and NPs act as carriers for various chemical and biological toxins and are ingested by zooplankton, bivalves, echinoderms—these move through the food web and damage the internal digestive system of living organisms. To eliminate the ecological threats, a bioremediation system is urgently required. Microorganisms like *Ideonella sakaiensis* are known to have enzymes that degrade plastic and can be useful as remediators. This chapter discusses the sources and transports routes of microplastics in the aquatic environment and their ecotoxicological effects on living organisms. Moreover, it highlights the bioremediation of environmental microplastics, its mechanism, and some necessary environmental policies to prevent it.

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13.1 Introduction

Plastic (from Greek "Plastikos") means malleable or moldable. It is considered an integral material at present due to its durability as a key attribute (Sharma and Chatterjee 2017). It is a versatile material due to its strength, low price, lightweight, and resistance to corrosion. They are known to have higher electrical and thermal insulation values. Currently, the most popular synthetic plastic materials are polypropylene (PP), high- and low-density polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET)—all together, they contribute to 90% of total production (Do Sul and Costa 2014).

Since the middle of the nineteenth century, several tonnes of plastics have been manufactured. Fast-forwarding to this day, plastic has gained a prominent place in the consumer market and is a ubiquitous component of modern life. According to the current trends, 25 billion of global plastic production has been predicted by 2050 (Yang et al. 2015). Tons of discarded plastics reach the environment through recycling, landfilling, or incineration and accumulate in the ecosystem. Eventually, plastic loses its mechanical integrity through biotic and abiotic pathways, and "microplastic" (MP) is introduced into the environment (Xu et al. 2020).

Microplastic is a predominant pollutant in both terrestrial and aquatic environments. This contaminant ends up in the environment and suffers fragmentation and degradation. Microplastic (MP) is defined by size ranging from 100 nm to 5 mm, and the size of nanoplastic (NP) is below 100 nm (Tang et al. 2021). Evidence of microplastic ingestion by marine organisms and subsequent transfer through trophic levels has been reported (Setälä et al. 2016; Pirsaheb et al. 2020). Nanoplastics are more hazardous in comparison as they are permeable to biological membranes.

This chapter will summarize the multidisciplinary overview of microplastic pollution in the aquatic environment. Though available literature relevant to this topic is vast, we will focus on some particular aspects such as classification and sources of microplastic and its toxicity in the environment.

13.2 Classification of Microplastics

13.2.1 Based on Size

Although Thompson et al. (2004) were the first to report microplastics, they did not specify the size based on which microplastic could be identified. However, several authors have set limits to distinguish between microplastic and macroplastic. Macroplastics are discarded plastic chunks visible to the naked eye among other sand and gravel (Malankowska et al. 2021). This criterion is of importance, because it helps differentiate between small macroplastic (one that can be detected using simple techniques) and microplastics (due to their much smaller size, it requires detection through optical instruments) (Costa et al. 2010). Collection, estimation of prevalence in the environment, and characterization of microplastics have been challenging due to their minute dimensions.

According to IUPAC (International Union for Pure and Applied Chemistry), the dimension of microparticles ranges between 0.1 and 100 μm (Vert et al. 2012). Nevertheless, in recent years, researchers have agreed that plastic particles having the longest dimension below 5 mm will be considered microplastic. Subsequently, countries of the Asia-pacific region, the European Union, the European Chemical Industry, and the EPA (United Stated Environment Protection Agency) collectively identify this criterion to be specific for microplastic based on various scientific reports (Wright et al. 2013). Along with microplastics, which are extensively explored as ocean contaminants, Andrady (2011) introduced a new concept, namely "nanoplastic," in 2011, which is identified as a product of the fragmentation of microplastic. After a few years, the upper limit for the size of nanoparticles was set to be 100 nm (Jambeck et al. 2015). This particular restriction is significant as plastic particles below this limit could have the potential to disrupt the cell membrane, which is not possible in the case of microplastics (Nguyen et al. 2019). With time and more investigation, many scientific communities have agreed on this size limit for nanoplastics. However, due to the scarcity of reliable literature, it is quite challenging to establish a perfect size limit and the hazardous effects of nanoplastics on living organisms.

13.2.2 Classification According to Origin

13.2.2.1 Primary Microplastics

Primary microplastics are defined as those which were originally fabricated as microplastics (Boucher and Friot 2017). These particles are added to various products such as air blasting technology, cosmetics, and scrubbers for facial cleansing (Derraik 2002). Other products like plastic capsules and vectors for medicines are primary microplastics themselves (Lindeque et al. 2020). Auta et al. (2017) gave other examples of products containing microplastic like cleanser, peelings, shower gels, eye shadow, foundation, mascara, blush powder, nail polish, hair colors, deodorants, shaving creams, bath lotions, baby products, sunscreen, mosquito repellants, etc. This depicts that personal hygiene and beauty-care industry, followed by the detergent industry, are the prominent manufacturers of products with added microplastic. According to a report, polyurethane is one of the common polymers that is manufactured as microplastic and it contributes to almost half of the total microliter coming from the cosmetic industry (Lei et al. 2017). These products are used by the population at large and lead to ultimate release into the environment. Other than this, microplastics are released into the environment during fabrication and maintenance of larger plastic products, that is, tires, synthetic textiles, paint, etc. (Shahnawaz et al. 2019).

13.2.2.2 Secondary Microplastics

Small plastic particles generated due to the fragmentation of discarded microplastic through biological, chemical, and mechanical processes are defined as secondary microplastics (Shahnawaz et al. 2019). The degradation process involved are biodegradation, thermo-oxidative degradation, photodegradation, mechanical weathering, etc. (Avio et al. 2017) (discussed in this chapter in another section). The breakdown of macroplastics increases their amount in the aquatic environment and becomes detrimental to aquatic organisms. Due to mass reduction in size, secondary microplastics get easily ingested in living organisms, making them susceptible to hazardous consequences (Law and Thompson 2014).

13.3 Distribution of Microplastic in Aquatic Environment

Microplastic pollution has heavily affected the aquatic environment. Reports of its presence in rivers, lakes, lagoons, coastal areas, and estuaries are available in the literature (Jiang et al. 2019; He et al. 2021; Sighicelli et al. 2018; Free et al. 2014; Quesadas-Rojas et al. 2021; Edo et al. 2020; Hantoro et al. 2019; Zhao et al. 2015). Microplastics are transported through the actions of rivers, wind, and ocean currents to beaches, shorelines, subsurface waters, and deep-sea sediments in remote locations (Eerkes-Medrano et al. 2015). The concentration of microplastics varies as per ocean currents distribution, depending on particle density and location of the sources. The consistent and buoyant nature of the particles helps them get dispersed widely through hydrodynamic processes (de Carvalho and Neto 2016). According to Cózar et al. (2014), the concentration was higher in the convergence zone of ocean surfaces. The sources and impacts of microplastics in aquatic environment are depicted in Fig. 13.1.

The abundance of microplastics in the aquatic ecosystem has been depicted through various surveys, including the polar region (Barnes et al. 2009), midocean islands (Martins et al. 2020), and deep-sea (Claessens et al. 2013). The omnipresent pollution by this contaminant in the Northeast Atlantic Ocean was demonstrated by Lusher et al. (2014). The average concentration of plastic was 2.46 particles m^{-3}. According to Desforges et al. (2014), the subsurface water layers of the northeastern Pacific Ocean contained microplastics with an average concentration of 4600 particle m^{-3}. According to their study, off-shore Pacific waters had microplastics in density ranging from 8 to 9200 particles m^{-2}, which was found to be increased by sixfold on West Coast Vancouver Island. The average abundance of the contaminating particles were in the range of 0–1.31 particles m^{-3} and 0–11.5 particles m^{-3} in the pelagic water layer of the Arctic Sea and south of Norway, respectively (Lusher et al. 2015a, b). The analysis of the particle composition depicted that they might be end- products from macroplastic degradation or wastewater effluent. Isobe et al. (2015) recorded a total particle density of about 1.72 million pieces km^{-2} in seawaters around Japan and East Asia (10 times and 27 times greater than the North Pacific and world oceans, respectively).

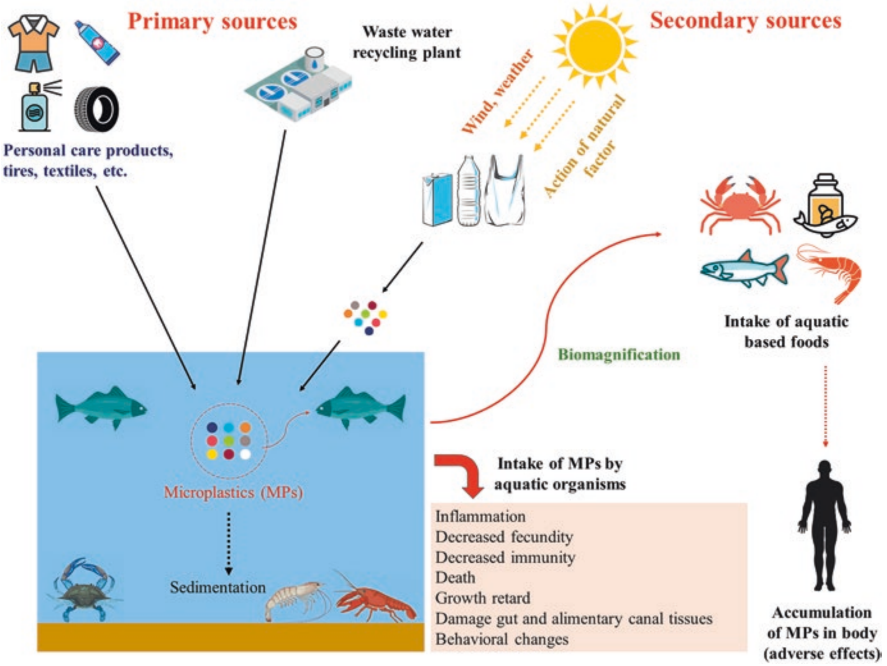

Fig. 13.1 Sources and implications of microplastics in aquatic environment

From the polluted subsurface waters, these particles accumulate in the sediments due to sinking. Various literatures support this theory and have reported high concentrations of plastic particles (in the range of 770–3300 plastic items kg^{-1}) in the sediments of the Rhine estuary and Wadden Sea (Cole et al. 2011). Microplastics concentration was denser in beach sediments (340.7–4757 particles m^{-2}) in comparison to the water column (204.5 and 1491.7 particles m^{-3}) on the south-east coast of South Africa (Nel and Froneman 2015). Fauziah et al. (2015) conducted a study at the sand beaches in peninsular Malaysia to quantify microplastic debris and found 2542 pieces (265.30 g^{-2}), which is an alarming number from a total of six beaches. Estuarine sediments from Vembanad lake of India (which is also a Ramsar site) were investigated to quantify microplastic particles by Sruthy and Ramasamy (2017). The range was 96–496 particles m^{-2} and the dominant polymer component for the pollution was low-density polyethylene.

In comparison to the marine environment, information regarding microplastic pollution in the freshwater environment is quite scarce. The source and transportation routes of this pollutant in this environment are diverse. Terrestrial, glacial, lacustrine, and marine environments are connected through the fluvial system, comprised of running water bodies. Rivers and streams play a highly dynamic role in accumulation and transportation of microplastics. They are connected with various pathways and release routes for the contaminant and are responsible for subsequent pollution. Jiang et al. (2019) investigated the pollution level in five rivers on the Tibet plateau. The surface water had a higher concentration of microplastics

(483–967 items m^{-3}) than the sediment samples (50–195 items kg^{-1}). Similar reports have been found in Indian rivers like Nethravati and Alakananda stretch, where sediments had less concentration of microplastics (Amrutha and Warrier 2020; Chauhan et al. 2021). On the other hand, Li et al. (2020) have depicted that the flowing water in the river might have less concentration of microplastic than the sediments; furthermore, sediments act as a temporary storage space for the contaminants. For example, during a study in Pearl river, China, it was found that sediments contained a higher density of microplastics, that is, 685 items kg^{-1}, in comparison to the column water (Fan et al. 2019). Hence, it is quite difficult to correlate the microplastic concentration in flowing water and static sediment. Lakes are another important component of the freshwater system. They receive microplastics through industrial effluent, surface runoffs, wastewater plants, etc., and rivers are the main carrier route of it. Lakes are complex systems that can potentially transport, disperse, or accumulate contaminants. Su et al. (2016) reported that the concentration of microplastics in Taihu lake, China, was 3.4–25.8 items L^{-1} and 11.0–234.6 items L^{-1} in surface water and sediments, respectively. Reports of heavily contaminated Lake Victoria, Africa, have been published (Egessa et al. 2020). The major pollutant resulted from microplastics' fragmentation, and the prime contributor was polyethylene (60%). Several studies have depicted a higher level of pollution closer to the population centers and have pointed out surface currents as the reason behind the dispersion of microplastics in the surface waters (Eriksen et al. 2013; Fischer et al. 2016; Dusaucy et al. 2021).

13.4 Degradation of Plastic in Environment

One of the prime features responsible for the versatility of a few synthetic polymers is resistance to environmental processes. However, this particular fact is the reason behind the very slow degradation process and longer residual periods for plastics in the environment. Plastic has hundreds or even more years of longevity depending on its properties and surrounding environmental factors (Anderson et al. 2016). Degradation is a physical or chemical transformation resulting in reduced molecular weight of polymer under environmental factors such as heat, light, moisture, or biological activity (Shah et al. 2008). The physical integrity of a polymer is affected by its molecular weight, and significant degradation of a polymer can weaken the material due to bond scission. Extensive degradation of plastic can even fragment it into powder form upon handling. Even these fragments can undergo further degradations through biological processes and result in "complete mineralization" (Urbanek et al. 2018). The degradation process is categorized into abiotic and biotic processes based on the nature of the causative agents.

13.4.1 Abiotic Degradation of Plastic

Abiotic degradation refers to changes in physical or chemical functionality of plastic due to the action of abiotic parameters such as air, water, light, heat, and mechanical processes. Usually, abiotic degradation occurs prior to biodegradation due to the scarce bioavailability of macroplastics (Andrady 2011).

13.4.1.1 Photo-oxidation of Plastic

Photo-oxidation is defined as the process of degradation of polymer by the activity of light. It is one of the primary factors that cause damage to the polymer in ambient conditions. Many synthetic polymers are susceptible to decomposition initiated by visible light and UV rays. Mainly, UV-A rays having medium energy (wavelength: 315–400 nm) and UV-B rays having high energy (wavelength: 290–315 nm) determine the lifespan of plastic in the outdoor environment (Jensen and Kops 1980). Most synthetic polymers are prone to absorption of high-energy radiation coming from the UV section of the spectrum, leading to activation of electrons and resulting in cleavage, oxidation, and decomposition. Degradation of microplastic occurs in the ether portions of soft fragments, and products with ester, formate, aldehyde, and propyl groups are formed (Singh and Sharma 2008). Photodegradation can alter plastic's physical, optical, and visual (yellowing) properties (Martin et al. 2003).

Ultraviolet radiation can successfully cause the cleavage of C–C bonds. The most damaging wavelength of UV radiation for a particular polymer depends upon its bond structure, and therefore, the value varies for different polymers. The required wavelengths for degrading polyethylene (PE) and polypropylene (PP) are 300 nm and 370 nm, respectively (Fernando et al. 2007). PE and PP absorb radiation, generating free radicals, which form hydroperoxides, the formation of which leads to the breakage of double bonds present in the backbone chain and the production of smaller degradation end-products (Yang et al. 2018). Phenyl rings present in polystyrene (PS) get excited upon absorption of UV radiation and form a triple-state, making it susceptible to decomposition. Alternating subunits of terephthalate and ethylene glycolate present in polyethylene terephthalate (PET) are linked through ester bonds. Upon photo-oxidation, the ester bonds cleave to form carbon dioxide, carbon monoxide, terephthalic acids, carboxylic acids, anhydrides, and esters (Fairbrother et al. 2019).

Decomposition initiated by UV irradiation is more effective in plastic exposed to air or the surface of a beach in comparison to plastic floating in the water. The reason behind the retarded degradation of microplastic in aquatic environment is the reduced temperature and oxygen concentration. Furthermore, the process is hindered due to fouling effects. Floating plastics develop surface fouling quickly; layers consist of biofilms of debris, algal mat, and colonies of invertebrates, respectively (Muthukumar et al. 2011).

13.4.1.2 Thermal Degradation of Macroplastics

Thermal degradation is the breakdown process of macroplastics by the action of energy that is generated from elevated temperatures. At high temperatures, plastic can undergo thermo-oxidative degradation. Long and complex polymer chains break when polymers absorb sufficient energy to surmount the energy barrier, generating reactive free radicals (Pirsaheb et al. 2020). They react with available oxygen and subsequently, hydroperoxides are formed, which in turn produce alkoxy radicals and hydroxyl free radicals in a process quite similar to the photodegradation of macroplastics. It is a self-propagating reaction that keeps on repeating unless the source of energy is cut off or inert end-products are produced by the collision of radicals. A vital difference between the photodegradation and thermo-degradation of plastics lies in the steps leading to the auto-oxidation cycle; another difference is that the former process occurs only on the surface of the polymer, whereas the latter process occurs throughout its structure (Tyler 2004).

The precise temperature required for this process varies among different polymers and is affected by the thermal characteristics (melting point and glass transition temperature) of plastic and the availability of oxygen in the environment (Crawford and Quinn 2016). The occurrence of exothermic oxidation in the environment is unlikely as the key requirement is high temperature. However, slowly progressing thermal oxidation of synthetic polymers may occur along with photodegradation in areas that are directly exposed to the sunlight. Kamweru et al. (2011) stated that temperature and ultraviolet radiation act synergistically on plastic decomposition. In another study, Kotoyori (1972) found that increasing humidity lowered the activation energy bar for the thermal decomposition of plastics.

13.4.1.3 Chemical Degradation of Macroplastics

Pollutants present in the atmosphere, such as ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), either directly cleave the chemical bonds within the structure of polymers or act as catalyzing agents in the formation of radicals by photochemical processes leading to degradation (Cooper and Corcoran 2010).

Ozone (O_3) is produced from oxygen (O_2) under the activity of ultraviolet rays and lightning. Its concentration is low in the atmosphere compared to the ground, where its concentration increases due to pollution by SO_2, NO_2, and VOCs (Placet et al. 2000). Even at lower concentrations, O_3 actively attacks the unsaturated double bonds present in the polymer structure, causing bond scission in the chain. In contrast to unsaturated polymers, O_3 reacts quite slowly with saturated polymers (Mohan et al. 2019). Sulfur dioxide (SO_2) can be excited upon absorbing UV irradiation, producing a singlet or triplet state that either readily reacts with unsaturated C–C bonds or produces O_3 from oxygen (O_2) through photochemical reactions. Nitrogen dioxide (NO_2) is also very reactive due to the presence of odd electrons in the molecular structure; hence, it reacts with unsaturated C–C double bonds in the polymer chain. Similar to SO_2, NO_2 is capable of producing O_3 from O_2 during the photochemical reaction (Min et al. 2020).

pH and salinity are the two most influential chemical parameters affecting the decomposition of macroplastics in the aquatic environment. A denser concentration of H^+ (responsible for lower pH) or OH^- (responsible for higher pH) can catalyze the hydrolysis of some particular synthetic polymers such as polyamides (PAs) (Wadsö and Karlsson 2013). These two parameters can also alter the surface properties of other macro- and microplastics and regulate their behavior in an aquatic environment and toward other pollutants present in water (Liu et al. 2019).

13.4.1.4 Mechanical Degradation of Macroplastics

The decomposition of plastics due to the activity of external forces is known as mechanical degradation. Examples of external forces are abrasion and collision of plastics with rocks or sands due to the activity of winds or waves. Freezing-thawing cycle of plastics in water can lead to mechanical degradation (Pastorelli et al. 2014). The mechanical properties of plastic determine the effect of outdoor forces. Among them, an important feature is “elongation at break,” which is defined by the ability of plastic to resist changes of shape without any tear or formation of crack (Krasilnikov et al. 2005). Plastics with lower elongation values at break are more prone to fragment under external tensile forces. Constant application of stress on plastics ultimately results in the breakage of chains in polymers (Sugimoto et al. 2020).

This kind of degradation is important for synthetic polymers. One of the major contributors of microplastics has been domestic washing due to the abrasion, shear, and stress on fibers during laundry (Cesa et al. 2020). Another noticeable source is abrasion of tire against road, which leads to scratching or microcutting of the tire and creating microplastics (Corcoran 2021).

Bond scissions and breakage of chains during decomposition by light, temperature, and chemical components affect the mechanical characteristics of macroplastics and precisely their tensile strength (Andrady 2017). O’Brine and Thompson (2010) found that environmental degradation processes reduced elongation values at the break of plastics, which subsequently decreased the need for external forces to fragment the plastics and enable the mechanical decomposition of macroplastics.

13.4.2 Biotic Degradation of Macroplastics

Biodegradation is a biochemical process that transforms compounds through complete mineralization by microbes. The end-products of the process are water and carbon dioxide under aerobic conditions and methane and carbon dioxide under anaerobic conditions. Microorganisms such as bacteria, fungi, insects, etc., are the prime agents for the biological decomposition of plastics (Crawford and Quinn 2016). Abiotic degradation processes, producing low- molecular- weight compounds, aid in eventual biotic degradation, as macromolecules could not be taken up and metabolized directly by microbes (Chen et al. 2019). Metabolites produced in this process are nontoxic to the ecosystem and are redistributed via nitrogen, carbon, and sulfur cycles (Cau et al. 2020). Though the source of biological degradation is microorganisms, nature is chemical; these chemicals are enzymes aiding in catalysis. The success of microbial action on polymers depends upon the availability of enzymes, the existence of a substrate site in the polymer for the enzymes to act upon, the specificity of the enzyme, and the availability of coenzyme if required (Reich and Stivala 1971).

Macroplastics are categorized into hydrolyzable and nonhydrolyzable based on the absence or presence of amide and ester functional groups, which can be attacked by extracellular hydrolases. Polymers like PE, PP, and PVC are identified as non-hydrolyzable, and the action of extracellular enzymes on them is complex. Santo et al. (2013) found the enzyme laccase released by actinomycete *Rhodococcus ruber* to be able to degrade PE. Hydroquinone peroxidase secreted by *Azotobacter beijerinckii* could degrade PS (Nakamiya et al. 1997). Hydrolyzable polymers like PET, PA, and polyurethane (PUR) are susceptible to biodegradation as extracellular hydrolases can act upon them (Chen et al. 2019). According to De Sá et al. (2018), PETase found in *Ideonella sakiensis* could hydrolyze PET in the environment. Enzymes like cutinase, serine esterase, lipase, and nitro-benzyl esterase are capable of hydrolyzing PET; on the other hand, cutinase, hydrolase, and amidase are involved in PA hydrolysis (Guebitz and Cavaco-Paulo 2008).

Oxidative and hydrolytic decomposition of plastics by different extracellular enzymes leads to chain breakage, generating polymers and fragments of short-chains (e.g., monomers, dimers, and oligomers). When the molecular weight of these fragments is small enough, they are taken up by microorganisms, assimilated, and subjected to subsequent intracellular metabolism (Wilkes and Aristilde 2017). Eventually, after both extracellular and intracellular pathways, mineralization results in the formation of carbon dioxide and water under aerobic conditions and in the formation of carbon dioxide, methane, water, organic acids, and ammonia under anaerobic conditions. Nonetheless, anaerobic biodegradation requires more time for complete mineralization than aerobic biodegradation (Gu 2003).

13.5 Sources of Microplastics in Aquatic Ecosystem and Transport Route

"Freshwater" indicates streams, rivers, lakes, and ponds, all of which have distinct features. The transport and retention of microplastics in the freshwater environment is a complex system. The freshwater environment acts as a conduit for microplastics entering into the system from the terrestrial region, acts as a hotspot for the production of microplastics through the degradation of macroplastics, and also acts as a basin retaining the plastic particles in sediments (Horton and Dixon 2018).

Disposal of waste in an inadequate manner leads to the release of macroplastics into the freshwater environment. The sources are general littering, wastes from landfills, or transportation from land via surface runoff. Apart from macroplastics, microplastics are significantly released into freshwater systems directly. Runoff and drainage from agricultural soils render ponds, lakes, and rivers contaminated with agricultural plastics, fibers, and microbeads (Steinmetz et al. 2016). Untreated and unfiltered urban runoff and storm drainage, containing road paint, particles of tires (generated from the collision between roads and tires), etc., pollutes the freshwater bodies (Treilles et al. 2021). Although wastewater treatment plants are used to remove microplastics, direct input of effluent-containing plastics into the water bodies can cause contamination (Murphy et al. 2016). During high flow, combined sewage overflows (CSOs) channel the untreated wastewater into nearby rivers to reduce the overpressure on drainage systems, inducing microplastic pollution in rivers.

Studies suggest that due to the drainage systems, water bodies act as more of a hotspot for pollution than the surrounding urban areas; thus, storm drainage, surface runoffs, inputs from CSOs, etc. should be controlled, and proper care has to be taken for their disposal (Horton et al. 2017). Along with rivers, other freshwater bodies like lakes and ponds receive wind-blown debris and land runoffs as inputs, and it gets accumulated over time due to their standing nature leading to burial and preservation within the sediments for a long time (Vaughan et al. 2017).

After entering the rivers, the particle of plastics is subjected to the same transportation system as the other sediments like sand and silts for mobilization. The speed of the water flowing in the river gives it energy, leading to the transportation of a greater portion of the particles (Knighton 2014). In the sections of the rivers where the energy drops and the flowing speed reduces, it is more likely for the plastic particles to settle down into the sediments. Additionally, the sedimentation helps in the burial of microplastics (Corcoran et al. 2015). Thus, the sediments would retain the microplastics throughout their movement through the freshwater systems (Nizzetto et al. 2016).

For all the microplastic wastes released from the freshwater and terrestrial environment (horizontal transportation), the oceans represent an ultimate sink (Lechner et al. 2014). After it reaches the oceans, they are dispersed widely and rapidly. Additionally, microplastics move through a vertical transport system via biofouling, incorporation in the marine snow, and excretion through fecal pellets (Rummel et al. 2017). This is considered vertical transportation. Apart from receiving inputs from rivers, oceans are contaminated with plastic by mismanaged fishing, which involves accidental cargo loss, illegal dumping, abandoned fishing nets, sinking of crafts, etc. (Xue et al. 2020). The major pollutant in these cases would be macroplastics, which will transform to microplastics and accumulate in the sediments over the years.

13.6 Ecotoxicological Impacts of Microplastics on Aquatic Ecosystem

Although various attempts have been made to evaluate the toxicity of microplastics to aquatic creatures, the impacts and mechanisms involved are still unknown (Desforges et al. 2014). Microplastics' potential toxicity can be attributed to three different mechanisms: (1) ingestion stress, such as physical blockage and expenditure of energy required for egestion, (2) additive leakage from plastic, such as plasticizers, and (3) exposure to toxicants involved with microplastics (persistent organic pollutants/POPs) (Cole et al. 2011; Andrady 2011). The consequences of microplastic exposure would be expected to differ depending on particle accumulation and translocation inside tissues, the organism's ability to ingest the particles, and the possibility of trophic transmission.

13.6.1 Impact on Aquatic Organisms

Phytoplanktons Any negative impact on the primary producers can eventually jeopardize a specific ecosystem's whole food web and food chain. It has been reported that exposure of phytoplanktons to microplastics can result in a stunted growth rate (Besseling et al. 2014). The negative impact of microplastics on algal development appeared to diminish as particle size rose (Zhang et al. 2017a, b). Physical interaction was found to be the cause of the impact of nanoplastic beads on two algae species, *Scenedesmus* spp. and *Chlorella* spp. When *Chlorella vulgaris*, *Dunaliella tertiolecta*, and *Thalassiosira pseudonana* were exposed to polystyrene particles with sizes ranging from 0.05 to 6 m for 72 h, no changes in algal growth were observed, but photosynthesis was reduced by 2.5– 45%. Contrastingly, Besseling et al. (2013) found that in the *Scenedesmus obliquus*, nanosized polystyrene particle (0.22 and 103 mg/l) exposure influenced algal development and reduced chlorophyll concentration, resulting in lower photosynthesis.

The effects of MPs have been documented in the marine ecosystem, with most scientific data indicating a possible effect of MPs at the producer level. After 96 h, exposure to polyvinyl chloride (PVC) MP (1 m size) lowered the growth rate by 39.7%, but 1 mm PVC had no harmful effect on *Skeletonema costatum* (Zhang et al. 2017a, b). In contrast, when *Tetraselmis chuii* was exposed to fluorescent red polyethylene microspheres (1–5 m) in the presence and absence of copper, no significant growth rate suppression was detected, suggesting that particle size was inversely proportional to MP toxicity (Davarpanah and Guilhermino 2015).

Zooplanktons Microplastics have been detected in rotifers, copepods, and cladocerans, which come in contact with microplastics through primary surface adherence and feeding habit (Jeong et al. 2016). Ingestion of 1 μm PE microplastics resulted in the immobility of the limnic *Daphnia magna* as concentration and time of exposure increased, according to Rehse et al. (2016), whereas the 100 μm that were not swallowed by *Daphnia magna* did not produce the physical impacts. *Calanus helgolandicus* copepods swallowed 11% fewer algae when exposed to 20 μm PS microbeads and cultivated algae, resulting in lower ingested carbon biomass and decreased fecundity (Cole et al. 2011). Differing sizes of microplastics can have significant size-related impacts on zooplankton, such as lower eating capacity, decreased fecundity and growth rate, increased mortality, lengthy reproduction time, and could even affect the next generation (Zheng et al. 2020). Smaller plastic particles, such as nanoplastics, are more toxic and damaging to zooplankton (Sun et al. 2017). Furthermore, the capacity of microplastics to be excreted may be directly proportional to their particle size. In brief, consumption of microplastics by zooplanktons revealed that primary consumers could directly interact with microplastics in the ecosystem.

Invertebrates Aquatic invertebrates feed directly on primary producers and serve as a valuable food source for the carnivores, which are significant ecological players. Aquatic invertebrates are more prone to microplastic pollution due to their feeding habits and position in the food chain as primary predators. Several reports have identified arthropods (De Sá et al. 2018; Arias-Andres et al. 2019), mollusks (Abidli et al. 2019; Teng et al. 2019) and worms (Li et al. 2019; Lv et al. 2019) as potent species for accumulation and transfer of microplastics into the next trophic level. Because of the abundance and toxicity of microplastics in bivalves like clams and mussels, the species has been considered a useful bioindicator for aquatic microplastic contamination (Ward et al. 2019). Furthermore, different aquatic invertebrate species have varied life properties, which has an impact on microplastic uptake models and dispersion in invertebrates. For example, microplastic uptake into the nonfilter-feeder marine shore crab might be facilitated by respiratory exposure (Watts et al. 2014). Furthermore, Kolandhasamy et al. (2018) discovered that adherence of microplastics to soft tissues of mussels causes microplastic accumulation and subsequent ingestion. Various negative impacts of ingested microplastic particles on the growth, feeding, development, survival, and reproduction of the invertebrates have been documented (Huvet et al. 2016; Foley et al. 2018; Trestrail et al. 2020).

Fish Microplastics can be ingested by fish either directly from the aquatic ecosystem or indirectly from their prey. Fish features (e.g., species, life phases, feeding behavior, and living habitat) influence microplastic intake the most, followed by exposure conditions, plastic qualities (e.g., kind, size, shape, color) and aging of microplastic biofilms (Neves et al. 2015; Ory et al. 2018; Collard et al. 2019). Lusher et al. (2013) investigated 504 fish from ten both pelagic and demersal species caught in the English Channel and discovered plastic waste (0.13–14.3 mm) in 36.5% of the fish digestive tracts, 92.4% of which were microplastics. As per a recent global analysis, 427 different fish species are present in all freshwater, brackishwater, and marine environments, while different food chain positions (i.e., herbivore, algivore, omnivore, carnivore, and detritivore) could ingest microplastics (Lima et al. 2021). Three distinct benthic fishes, that is, *Cleisthenes herzensteini*, *Liparis tanakae*, and *Lophius litulon* collected from 14 different spots of the South Yellow Sea, were found with microplastic concentrations of 19.2, 27.5, and 5.9 particles g^{-1}, respectively (Wang et al. 2020). According to this finding, it can be concluded that microplastics had significantly contaminated the surface sediments and benthic species. Microplastics can interact with fish in various ways, including direct feeding, transfer in levels of the food chain, respiratory exposure and absorption through the skin, but their distribution in fish is difficult to predict. Hotspots for primary plastic accumulation are gastrointestinal tracts and gills (Barboza et al. 2020; Jaafar et al. 2020; Koongolla et al. 2020); especially nanoplastics are transported to various tissues and organs via complex mechanisms due to their smaller size and membrane permeability (Jacob et al. 2020; Guerrera et al. 2021; Ma et al. 2021). Microplastics in fish can affect the histological function and produce gastrointestinal obstruction, leading to reduced feeding. The very fine-sized microplastic may be absorbed through the intestinal lining as it passes through the gastrointestinal tract and eventually enters the bloodstream, translocates to other organs, and threatens survival (Barría et al. 2020). Other severe impacts are dysfunctionality of gills, disruption in neuromuscular functions, and rendering the fish vulnerable to plastic toxicity (Chen et al. 2021).

13.6.2 Toxicity from Contaminants Associated with Plastic

Microplastics' enormous surface-to-volume ratio and hydrophobicity allow them to accumulate harmful chemicals in water (e.g., heavy metals and persistent organic pollutants) at concentrations far greater than in ambient water (Mato et al. 2001; Holmes et al. 2012). Furthermore, several additives, such as bisphenol A, alkylphenols, phthalates, and polybrominated diphenyl ethers, are commonly used in the manufacture of plastics to improve the performance of the final product (Barnes et al. 2009). These plastic additives may have hazardous effects on the aquatic biota after they have leached out. Colonization of the plastic by potentially hazardous microbes could endanger the aquatic food web (Zettler et al. 2013). Despite the fact that microplastics are biochemically inert, the leaching of plastic additives and the buildup of other toxicants and pathogenic bacteria turn them into a complex cocktail of dangerous compounds (Hossain et al. 2019). The ingestion of contaminated microplastics by aquatic creatures provides a viable route for these dangerous compounds to enter the aquatic food web. Microplastics, in combination with noxious chemicals, have the potential to cause neurotoxicity (Avio et al. 2015), organ disease (Bhatt et al. 2021; Du et al. 2021), metabolic disorders (Ye et al. 2021), and mortality in aquatic biota (Phothakwanpracha et al. 2021). However, whether ingesting microplastics promotes the transmission of toxicants to aquatic organisms is still debatable, especially when compared to other exposure paths.

13.7 Bioremediation Aspects of Microplastics

Biodegradation is the breakdown of organic substances by living organisms, and this process is referred to as environmental remediation or bioremediation when it occurs in conjunction with the ecosystem and waste management (Masiá et al. 2020). The type of polymer, its characteristics, the type of organisms used, and the pretreatment form are the prime influencers of the biodegradation process. In the degradation process, the molecular weight of the polymer and the additives coated with the polymer play a major role (Artham and Doble 2008). The rate of degradation is reciprocally propositional to the molecular weight of the polymer. The degradation rate for some plastics, such as polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB) and polylactic acid (PLA), is higher in comparison to synthetic polymers, such as polyethylene (PE), polycaprolactone (PCL), and polystyrene (PS) (Sivan 2011).

Biodeterioration, biofragmentation, assimilation, and mineralization are the four phases in the biodegradation process. The biodeterioration process begins with creating a biofilm surrounding the plastic polymer, signaling the start of the degradation process. Microbes manufacture the extracellular enzyme in the second stage, which acts on the polymer, converting it into an oligomer, dimer, or monomer, and preparing it for easy ingestion. In the third step, the oligomer/dimer/monomer assemblage on the surface of microorganisms is absorbed by microbial cells by simple diffusion or enhanced diffusion. The formation of daughter metabolites such as CO_2, H_2O, and CH_4 is the final stage (Lugauskas et al. 2003; Tokiwa et al. 2009). Each microorganism has the ability to destroy microplastics through the techniques described above. However, each microbe has the ability to release a unique enzyme for microplastic breakdown. It differs for microorganisms depending on their environment. Tanasupawat et al. (2016) reported the isolation of *Ideonella sakaiensis* bacteria from a PET-polluted environment. Palm et al. (2019) have revealed that this bacterium secretes the two enzymes responsible for PET breakdown: PETase and MHETase. Some bacteria can multiply on the flat substrate of plastic items, using them as a carbon source and forming a biofilm around them (Zettler et al. 2013). These bacteria use specific enzymes to break down the synthetic polymer into monomers. Skariyachan et al. (2021) recently reported the use of a bacterial consortium (*Pseudomonas* and *Enterococcus sp.*) to decompose microfragments of LDPE and PP.

Alcaligenes faecalis, *Pseudomonas stutzeri*, and *Streptomyces* sp.—all have polyhydroxyalkanoate (PHA) depolymerase (Jendrossek and Handrick 2002; Kadouri et al. 2005). Basidiomycetes, Deuteromycetes (*Penicillium* and *Aspergillus*), and Ascomycetes are the most common PHA-degrading fungus isolated from soil and marine habitats (Egbeocha et al. 2018). Polycaprolactone (PCL) is synthetic polyester that is quickly destroyed by the bacteria *Alcaligenes faecalis* and *Clostridium botulinum* and the fungus *Fusarium* (Grigore 2017; Egbeocha et al. 2018; Li 2018). Polylactic acid (PLA) is a polymer commonly used in biodegradable plastics; it has been shown to be degraded by a thermophilic bacteria (*Bacillus brevis*) (Duis and Coors 2016), as well as by only two *Fusarium moniliforme* fungus strains and *Penicillium roqueforti* (Egbeocha et al. 2018).

Other than microbes, the potential of various plants and animals is being researched for bioremediation of microplastics. Higher eukaryotes such as vertebrates, cephalopods, and decapods, which have been reported to be vulnerable under stress, should not be used in bioremediation. Second, microplastics should be captured, retained, and filtered/ingested at higher rates, as should their digestion/elimination; they should not be released into the environment. Species should only be used within their indigenous range, as geographical migrations must be avoided for the sake of biodiversity conservation (Molnar et al. 2008). Species with a wider distribution and easier control and management are considered potential candidates.

Microplastic retention appears to be a possibility for filter-feeding organisms. *Mytilus* mussels are pollutant-retention organisms that help bioremediation in natural habitats (Broszeit et al. 2016). Microfragments of plastics can be kept in their circulatory system for 48 days (Browne et al. 2008); nevertheless, most microplastic fibers are expelled after 24 h, compromising their elimination efficiency (Chae and An 2020). Adherence to the coral surface appears to be an effective strategy for MPs retention in other filter-feeders such as cnidarians (ingestion rates were 0.251–14.810 particles/h, whereas surface adhesion was 40 times larger; Martin et al. 2019). The sandworm *Arenicola marina* has a lifetime retention rate of 240–700 MPs (1.2 ± 2.8 particles/g), which appears to have no effect on its metabolism (Bansal et al. 2021); it could be a candidate for environmental remediation in oceanic and brackish waters, because it can tolerate salinities as low as 12 ppt. The echinoderm sea cucumber (recommended for pollution monitoring) is another intriguing organism that may be appropriate for eliminating PCB-contaminated plastic, since it preferentially ingests microplastics over other sediment particles (Alava 2019).

Higher plants have the greatest advantage over animals in that there is no sign of suffering. The bioremediation capability of algae, specifically microalgae, has been investigated in water. Roccuzzo et al. (2021) depicted that unicellular microalgae may digest endocrine-disrupting substances in wastewaters when used alone or in combination with bacteria. Seagrasses, which can grow in marine and brackish habitats, are of interest in cleaning effluents near the sea. The smooth ribbon seagrass *Cymodocea rotundata* was proposed by Huang et al. (2021a, b) for bioremediation of textile dye wastewater. Microplastics can be retained in a variety of ways in seagrasses and higher plants, with the particles collecting on the blades along with their associated bacteria. Plastic particles are found in epibiont communities on the blades in the seaweed *Thalassia testudinum* (Goss et al. 2018), but synthetic microfibers have been identified adhering to blades without epibiont communities in the seaweed *Fucus vesiculosus* (Goss et al. 2018; Gutow et al. 2016). Ali et al. (2020) recommended many freshwater Magnoliophyta (having heavy metal removing capability) for removing microplastics from WWTPs, including water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), and duckweed (*Lemna minor*). Nano- and microplastics do not appear to constitute an ecological concern to aquatic macrophytes in environmentally realistic quantities. Some macrophytes, including *Egeria densa*, and their microbiomes have been shown to collect and convert gold nanoparticles (Avellan et al. 2018); these systems could be studied for MPs bioremediation.

13.8 Development of Regulations and Policies

Plastic production has been increasing exponentially for decades, and it appears that the number of microplastic particles will continue to rise in the coming years. The original sources and classifications of plastics and microplastics entering the marine environment must be recognized to reduce the introduction of microplastics into the aquatic ecosystem. Also, raising public awareness about microplastics through education in the public, private, and government sectors will go a long way. Raw water, groundwater, bottled drinking water, and food items have all been discovered to contain microplastics (Koelmans et al. 2019; Rainieri and Barranco 2019; Jadhav et al. 2021). However, no microplastic contamination criteria have been established, and no parameters have been designed to assess the microplastic limit in drinking water. As a result, a number of organizations, government agencies, institutes, and authorities working on new pollutants must concentrate on determining microplastic limits in various resources and their potential repercussions. Microfibers and microbeads are predominantly secondary microplastics produced by washing garments; as a result, policy implications must be established to filter and catch these microplastics before they contaminate the natural ecosystem (McDevitt et al. 2017). Aside from that, corrective methods to limit and control plastic and microplastic debris with public participation must be implemented. To reduce microplastic and plastic pollution in the natural environment, comprehensive and effective measures must be implemented.

Concerns about microplastics have prompted numerous groups to propose management standards. The United Nations Environmental Programme's (UNEP) Expert Panel has called for prompt action to clear the oceans of microplastics, citing that microplastics are swallowed by a huge number of marine organisms, causing them physical and chemical harm (Wu et al. 2017). Similarly, the UNEP-MAP (United Nations Environment Program/Mediterranean Action Plan), OSPAR (the Oslo/Paris Convention—for the Protection of the Marine Environment of the North-East Atlantic), and HELCOM (Baltic Marine Environment Protection Commission—Helsinki Commission) have developed guidelines for assessing marine litter, including microplastics (Karbalaei et al. 2018). Nongovernmental organizations (NGOs) have also presented initiatives to raise awareness and assist in quantifying the extent of MPs pollution and its consequences on a national and international scale.

Many regions have established or implemented regulations prohibiting the manufacture and use of primary MPs, such as microbeads, which could minimize MPs entering the aquatic system (CEPA (Canadian Environmental Protection Act) 2016; Beat the Microbead 2016; United Kingdom Department for Environment, Food and Rural Affairs 2016) (Wu et al. 2017), as well as restrictions on the use of single-use macroplastics (i.e., bottles, carrier bags). The Netherlands was the first country to declare its intention to create microbead-free cosmetics, with a 2016 deadline (Ogunola et al. 2018). According to Kamat and Kamat, China has outlawed nonbiodegradable bags and single-use straws in all cities. Korea, meanwhile, prohibited microplastic-based cosmetics in 2021. Some nongovernmental organizations (NGOs) and businesses identified microplastic-free products and promoted the certificates "Good Scrub Guid" (Flora and Fauna) and "Zero plastic within" (product label) (Jeyavani et al. 2021). Bio-based plastics have recently been employed by China and American (USA) customers in place of plastic products. According to Kamat and Kamat, the Indian government announced in 2018 that single-use plastics would be phased out by 2020. One-time used plastic bags, cutlery, and some PET bottles were all banned in India in June 2019. The airport administration certified 55 of the country's 134 airports to be plastic-free. The government of Himachal Pradesh has outlawed the disposal of plastic products (plastic cups and plates) since 2017, resulting in a significant reduction in plastic pollution (Kamat and Kamat 2021).

13.9 Conclusions and Future Perspectives

Because of their longevity and slow rate of deterioration, plastic materials survive in the environment. It has been changed into microplastics due to natural forces, which easily enter all ecosystems and, as a result, into living beings, where it accumulates, magnifies, and causes damaging consequences. Microplastics are easily swallowed by marine organisms due to their small size and have been reported to concentrate in tissues, the circulatory system, and the brain. This chapter highlights these important aspects of microplastics in an effort to promote coherent literature and future research among scientists interested in this field. Microplastics cannot be reduced without the general population's participation, the socioeconomic sectors, tourism, and waste management companies.

Microplastics are predicted to have a greater negative impact, because most countries lack sewage treatment infrastructure and have yet to minimize, repurpose, and recycle plastic products. Appropriate technological solutions must be implemented, and knowledge of waste segregation at the source and the need for plastic recycling must be raised. Strategies to limit the input of plastic into the biosphere should be included in the management protocol. Specific approaches should be used to treat primary and secondary microplastics and keep them out of the ecosystem. Furthermore, there are little research on the prevalence, fate, toxicology, and reduction of MPs in India, necessitating the scientific community's attention for further investigation.

Flaws in waste management must be addressed in order to improve current procedures and reduce the risks connected with them. Furthermore, several bacteria are being tested with properties that could degrade microplastics of aquatic origin. These microorganisms might potentially be used to clean up contaminated settings. The use of microbes for microplastic degradation is a potential and environment-friendly action plan that will allow for the management of microplastics without negative consequences and eventually support the natural clean-up of contaminated areas.

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