Journal of Applied Biology & Biotechnology Vol. 10(5), pp. 66-75, Sep-Oct, 2022
Available online at http://www.jabonline.in
DOI: 10.7324/JABB.2022.100508

Emerging microplastic contamination in ecosystem: An urge for environmental sustainability

Akanksha Saini, Jai Gopal Sharma*

Department of Biotechnology, Delhi Technological University, Shahbad Daulatpur, New Delhi, India.

ARTICLE INFO

Article history:
Received on: January 18, 2022
Accepted on: March 30, 2022
Available online: July 20, 2022

Key words:
Environment,
Human health,
Microplastics,
Pollution,
Toxicology

ABSTRACT

Plastic use has increased steadily in recent years due to the urbanization and industrialization at global scale. Due to the population expansion, more plastic products are being utilized in today's scenario. Most of the plastic waste generated is due to its single usage that finds its pathway in oceans, seas, rivers, ponds, and landfills. Plastic waste on degradation produces microsized plastic (diameter <5 mm) termed as microplastics (MPs). MP contamination in environment is facilitated through various sources including cosmetic products, drug carriers, glitters, and disintegration of larger plastic products such as water bottles and fishing net. Due to their ubiquitous use in the environment, they possess serious threat to terrestrial and aquatic environments and human health. Many countries have already established regulations such as ban of single-use plastics and Microbeads-Free Waters Act to control its pollution and impacts on organisms. This review explores thoroughly the interactions of MPs with other pollutants, toxicological effects of the MP additives, occurrences of MPs, and impacts on the soil stability, structure, organisms, marine species, plants, and human health. This review also covers the strategies and regulations that are implemented to mitigate the MPs pollution.

1. INTRODUCTION

Over the past few years, accumulation of plastic is increasing in the environment due to its unfeasible use and disposal along with its low degradation rate. In 2018, approximately 360 million metric tons of plastics were produced globally and it is expected that by the year 2050, the global production would be up to 33 billion tons [Figure 1]. Around the world, China is the largest producer of the plastics and it has the highly polluted water bodies also [Figure 2] [1]. The Yangtze River, China, is the highly polluted river having approximately 310,000 tonnes of plastic, followed by the Ganga River, India, which is having 115,000 tonnes of the plastic waste [2]. Apart from that, the current outbreak of COVID-19 has also increased the production of plastics as in the personal protective equipment (e.g., gloves and masks) plastics and rubbers are the main components. Furthermore, up until 2015, 6300 million tons of plastic were discarded as a waste and around 79% of waste was piled up in the landfills or in the natural environment and it is expected that the amount of waste would increase significantly in the future, that is, up to 12,000 million tons by 2050, if management would not take actions immediately**.**

Microplastics (MPs) can be defined as the plastics, having size ranges from 1 μm to 5 mm and irregular or regular in shape, which are basically insoluble in the water. These particles have been commonly detected in a wide range of shapes, such as microbeads, fibers, nurdles, fragments and foam, and sizes that are based on their continuous breakdown, that is, large MPs (range: 1–5 mm), small MPs (range: 0.3–1 mm), and nanoplastics (<0.3 mm) [3]. Various studies have been done which highlighted the presence of MPs in different environments such as marine environments, rivers, beaches, lakes, soil, air, and other environments. For example, in the Dongting Lake, China, the concentration of MPs ranges from 900 to 2800 particles/m^3 in concentration whereas in the North Atlantic Ocean, it is 2.46 particles/m^3 [4,5]. MPs can be generated from sources including effluents discharge, dumping of garbage, agricultural waste, and human activities. On entering into the environment, its properties are influenced by its density as well as adsorption of biotic or abiotic substances onto its surface that can also be responsible for the physical and physiological toxicity caused by it, to the organism upon its ingestion. Similarly, behavioral changes due to the exposure of MP pollutants in marine ecosystem are also observed including physical, chemical, and biological attributes [6]. Furthermore, MP pollutants in the agricultural ecosystem affect the soil stability, molecular characteristics, plant growth parameters, and adverse impact on soil microorganisms [7]. MP pollution has detrimental effects on different countries with the most polluted being Maldives, reported in a recent study. The concentration of MP contaminants found in the Maldives is estimated to be around 55–1127.5 MP/kg. This value is approximately found to be greater than the MP pollution found at Tamil Nadu, India (3–611 MP/kg). Neighboring countries, such as India, were also a major contributor to these pollutions. Apart from that, poor wastewater

**Corresponding Author:*
Jai Gopal Sharma,
Delhi Technological University, Shahbad Daulatpur,
Main Bawana Road, New Delhi, India.
E-mail: sharmajaigopal @ dce.ac.in

and sewage system were also responsible. It is believed that speedy refinement in waste management and notable reduction in waste could help with the MPs pollutions in these small islands [8]. Therefore, MPs alone or with other pollutants can possess great impact on the ecosystem for longer duration due to its low rate of degradation. Most of the studies that have been published have focused their attention on a specific type of ecosystem without explaining the overall impact of MP on environment. Thus, it is necessary to understand and comprehend the major problem of MP accumulation in various environmental conditions with detrimental effect on soil, air, water, and human beings. Therefore, this review aimed to: (1) Present the different sources and chemical composition of the MPs; (2) summarize interaction of MPs with abiotic and biotic pollutants; (3) explain toxicological effects of the MPs and its additives on the environment; (4) elucidate occurrences and impacts of MPs on various environment; and (5) discuss the strategies and regulations that are taken for the control of MPs pollutions.

2. CHEMICAL COMPOSITION OF THE MPS

The main components of the MPs are the polymeric raw materials like monomers and the chemical additives. The basic units of plastic polymers commonly known as monomers produce biochemically inert structure. Commonly used monomers include polyethylene terephthalate (PET), high- and low-density polyethylene (HD/LD-PE), polystyrene (PS), polyvinyl chloride (PVC), and polypropylene (PP). Lithner *et al.*, 2011, in his study, have ranked the polymers according to their hazardous properties and further found that the styrene polymer is a potential carcinogenic or mutagenic carrier and is one of the most hazardous polymers [9].

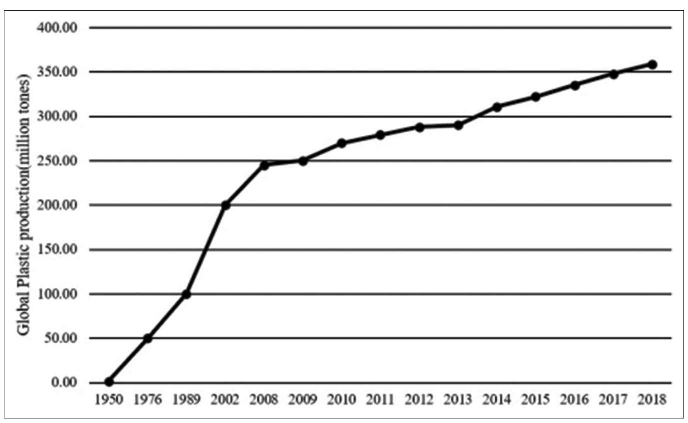

Figure 1: Global plastic production, 1950–2018.

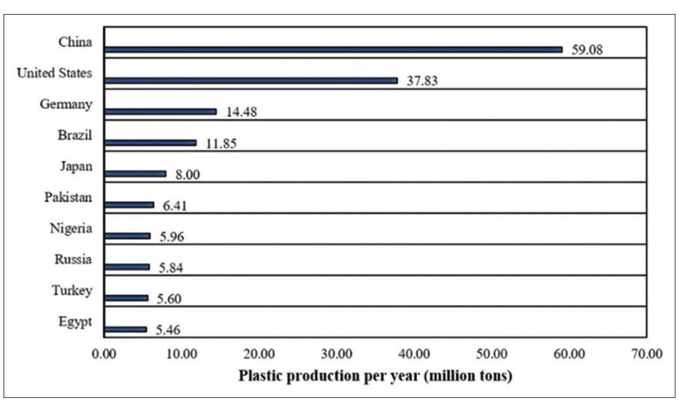

Figure 2: The countries with most plastic pollution.

Other component of the MPs is the chemical additives that include flame retardants, plasticizers, antioxidants, fillers, dyes, UV, and heat stabilizers and lubricants. By the formation of an ash layer or by the prevention of oxidation of flammable gases, flame retardants are basically used to protect or cool down the material in case of fire event [10]. Plasticizers are the complex chemical compounds having properties such as low vapor pressure, chemical stability, and are insoluble in the liquids. They are used to enhance workability, distensibility, or mobility of plastic. Fillers are of two types, that is, inert fillers, which are used for modifying the working, strength, shrinkage and flow properties, and reinforcing filler, that are superior to the base resin because of their strength. Soluble or insoluble dyes are the substances having organic or inorganic material in the form of fine powders that are used to give the desirable color to the polymer. UV and heat stabilizers are added to protect the plastics from degradation by light, heat, or UV radiations. By improving the flow characteristics of the plastic material, lubricants help in the facilitation of plastic processing. Table 1 depicts the examples of the additives that are commonly used for the production of the plastics.

3. SOURCES OF MPs

Depending on the source of the MPs, they can be classified as primary MPs and secondary MPs. The primary MPs are mainly the MPs that are released from the products containing MP such as plastic microbeads and nurdles that are the pre-production plastic pellets used for the manufacturing of the plastic products. The microbeads that are made up of polyethylene (PE) can be used as an exfoliants, in the cosmetics products, scrubs and toothpastes, and drug carrier, which make them a potential source of primary MPs that are added in the environment after its use by the consumer [11]. Furthermore, a recent study has highlighted that the glitters that are often used in crafts, cosmetics, and textiles are an important source of the primary MPs pollution. Another type of the MPs based on its source is the secondary MPs that are basically the fragments of the plastics that are generated on the degradation of the larger plastics products, such as rope, clothing, and packaging products, through chemical, physical, or/and biological processes. These plastics on degradation are directly or indirectly ingested by the organisms, leading to inflammatory responses and blockage in the gastrointestinal tract (GIT) [12]. Some common sources of secondary MPs include fishing nets, water bottles, soda bottles, tea bags, and microwave containers.

MPs have been widely used in industries including textile, automobiles, electronics, and paints, from there they can be directly discharged into the water and thus affect the aquatic ecosystem. Another source of the MPs is the plastic fibers that are used in the textile industry, as several clothes are made up of these fibers which on washing can release its ultrafine particles in the environment. Other well-known sources include the plastic film that is widely used in the agricultural sector, tires, paint particles, polymeric materials used for drug delivery, waste generated by the ship in the water, and plastics food packaging products [2,13]. In addition, sources of the MPs in the air are the industrial emissions, degradation of larger plastics material, particles that are released from the traffic, waste disposed in the landfills, and resuspension of road dusts.

4. INTERACTION OF MPS WITH POLLUTANTS

4.1. Interaction with Biotic Pollutants

MPs can act as a host for the microorganisms such as bacteria, algae, and viruses. These microorganisms can attach onto the outer surface

Table 1: Examples of commonly used chemical additives for plastic production.

Chemical Additives	Examples
Plasticizers	Phthalates, polymeric polyesters, carboxylic acid esters, etc.
Flame retardants	Chlorine, bromine, aluminum hydroxide, phosphorus, etc.
Fillers (inert or reinforcing)	Clay, chalk, glass, carbon black, carbon nanotubes, talc, etc.
Dyes	Heavy metals, azo dye, phthalocyanine dye, various chromophores, etc.
Lubricants	Calcium or manganese stearates.
UV or heat stabilizer	Inorganic or organic cadmium, barium, or lead salts.

of the MPs and then enter into the food chain causing harm to the other organisms. The reason for the adhesion and growth of the microorganisms on the MPs are MPs provide a more appropriate environment for the growth of the immobile microorganisms as compared to a planktonic life and the inorganic and organic nutrients or substances that are adsorbed onto the surface of the MPs, provide a suitable support for the growth of the adhered microorganisms [14]. In one of the studies, it is estimated that the total amount of approximately 1000–15,000 tonnes microorganisms can adsorb onto the surface of the marine MPs [15]. Other studies have highlighted that microorganism can quickly cover the surface of the MPs when entering into the ocean and then form a stable biofilm in around 7 days. These biofilms can then attract other zooplanktons to attach on the surface of the MPs [16]. Comparative to MPs alone, the degradation of the MPs after the attachment of the microorganisms will be more difficult and has more harmful effects on other organisms.

4.2. Interaction with Abiotic Pollutants

Due to its chemical and physical properties, MPs can adsorb various chemical contaminants that are present in the environment, such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, organochlorine pesticides, antibiotics, and heavy metals. The previous studies have shown that the MPs have higher concentration of pollutants onto it, as compared to the surrounding, due to its strong sorption capacity [17]. They accumulate higher number of pollutants due to its large surface area and same hydrophobicity as organic pollutants. Due to the varying physical and chemical properties of the plastics, the adsorption of pollutants onto the plastic is different for different plastic type. PE is more capable of adsorbing organic contaminants with varying hydrophobicity, whereas the polyamide has high affinity for trimethoprim as compared to PE and PS [18]. Furthermore, the adsorption rate and capacity of the MPs are affected by the size of the MP. Therefore, the nano-sized and micro-sized plastics can adsorb more pollutants than the millimeter-sized plastics because of their larger surface area [19].

The adhesion of the pollutants onto the MPs makes it a potential source of pollution which can migrate to the surrounding environment through external forces such as wind and water. Furthermore, the microorganisms that are attached onto the MPs can migrate through the same force and thus increase the risk of biological invasion. Therefore, MPs can possess more risks to the environment.

5. TOXICOLOGICAL EFFECTS OF MPS AND ITS ADDITIVES

Long-chain organic polymers are the building block of the plastics. These polymers are not considered very hazardous to the environment because of its large molecular size which makes them biochemically inert. Many hazardous substances such as monomers, chemical additives, and its degradation product or by product could be released throughout the life cycle of the plastics. Based on the composition of the monomers, the most hazardous type of polymers are polyurethanes, PVC and polyacrylonitrile. On the other hand, polyvinyl acetate, PP, PE, and ethylene-vinyl acetate are considered as the least hazardous type of the polymers. Some monomers have harmful effects on humans such as vinyl chloride and styrene monomers both have shown mutagenic and carcinogenic effects, whereas bisphenol A (BPA) monomer disrupts the endocrine function. Contrary to that, monomers such as ethylene and propylene are considered as least harmful to humans [20]. In one of the studies, it is found that air pollution can be caused by the volatilization of chemicals that are released from the polymers such as styrene, formaldehyde, and vinyl chloride [21]. Food and beverage industry commonly used polymers are PET, polycarbonate (PC), and HD-PE. Some studies have shown that BPA is released from the PC polymer which is associated with various human health problems such as type-2 diabetes, obesity, reduced sperm production, cardiovascular diseases, and increases the chances of breast cancer and prostate cancer [22]. On the other hand, uptake of PET by the human can lead to health problems such as chronic pneumonia, allergy, asthma, and gastrointestinal obstruction [23]. In case of PVC, phthalates are used to make them flexible, which are harmful to the human health as they can cause skin disease, ulcer, vision failure, genetic abnormalities, and birth defects [22].

Additives are added to the plastics, during its production, to improve its properties such as strength, workability, and UV or heat resistance. These additives have several toxicological effects also, as they are not always bound to the polymer of the plastics [13]. In case of MPs, this release of additives is more effective due to its large surface area to volume ratio. In addition, various additives are highly toxic, such as PBDEs (heat resistant) and nonylphenol (antioxidant) [24]. Furthermore, additives are released more often in areas where there are more concentrated MPs, where plastics and its components are exposed to UV and areas having higher temperatures [13]. Phthalates (plasticizers), due to its ability to alter the endocrine function of the body, can affect the development of the amphipods and crustaceans, reproduction of animals and can also induce genetics aberrations [25]. Plasticizers are highly toxic to plants also, for example, tetrachlorophenol, a heat-resistant thermoplastic, is directly toxic to the phytoplankton. The toxicological effects on human health are still in its initial stage. Many studies have highlighted that the consumption of fish containing MPs by the humans can cause health problems such as inflammation and cell necrosis [26]. Furthermore, ingestion of the food contaminated with MPs can cause serious problems to the humans as well as to the organism positioned at the top of the food chain.

6. OCCURRENCE OF MPS IN VARIOUS ENVIRONMENTS

6.1. Marine Water

Presence of MPs has been reported in marine systems globally. Commonly found polymer type of MPs in the marine systems is the PS, PVC, PE, PP, and polytetrafluoroethylene. About 80% of the plastic waste that is present in the ocean is the land-based plastic debris that enters through shipping, activities related to fishing, and aquaculture as well as through rivers, beach littering, and atmospheric transport [27]. In addition to that, natural disasters, like hurricanes, strong sea and tsunamis, can also cause the transport of large number of MPs to the marine environment. WWTPs can also contribute to MPs pollution into the ocean by either releasing the effluents or by releasing it into the sea via river. In Northwestern Pacific Ocean, the surface waters are polluted with the MPs with concentration ranging from 640 to 42,000 items/km^2 whereas, in the Arabian Bay, the surface waters account for the MPs concentration ranges from 4.38×10^4 to 1.46×10^6 items/km^2 [28,29]. Furthermore, Song *et al.*, 2018, have shown that the concentration of MPs was higher in the urban coastal regions of South Korea, that is, 1051 particles/m^3 as compared to the rural coastal area, that is, 560 particles/m^3 [30]. In the sub-water of Northeast Greenland, the concentration of MPs accounts for 1–3 items/m^3 whereas, in the vicinity of Antarctic Peninsula, it ranges from 755 to 3524 items/km^2 [31,32]. Moreover, Zhang *et al.*, 2019, had investigated the concentration of MPs in 25 samples of sediments collected from the Yellow Sea and East China Sea, China, and found that the average concentration of MPs at these 25 sites was approximately 13.4 particles/100 g dry weight [33].

6.2. Freshwater

The release of MPs in freshwater occurs due to incomplete MPs retention in the sewage sludge or due to MPs being filtered out during sewage treatment process. Some common sources of MPs in the freshwater are the plastic resin powder originated from the industries, personal care products containing microbeads, pellet spillage from the air blasting machine, plastic raw materials used for the production of plastic products, as well as the secondary MPs. In Denmark, storm water ponds that receive water from the urban runoff were reported to have MPs concentration of up to 22,849 MPs/m^3 [34]. Snake River in North America was found to have the highest peak concentration of MPs of about 5,405,000 MPs/m^3, followed by Saigon River in Vietnam having MPs concentration of 519,223 MPs/m^3 [35,36]. Furthermore, a study was conducted by Alam *et al.*, 2019, to investigate about the presence of MPs near Ciwalengke River, located in the slum areas of Majalaya, Indonesia. He found that, on average, MPs of concentration 5.85 particles per liter of surface water were present and most of them were fibers which could be originated from the cloth washing of locals in the river [37]. Moreover, it is reported that wastewater treatment plants (WWTPs) can efficiently remove up to 95% of the MPs and along with that tertiary treatment can also efficiently remove 90% of the fine size particles having size larger than 10 μm [38]. However, a recent study has found that even the higher removal efficiency of the WWTPs cannot offset the number of MPs that are released into the freshwater through WWTPs and thus making WWTPs a source of MPs [39].

6.3. Soil

Soil acts as an important reservoir for the MPs. The previous studies have shown that MPs can be found in sewage sludge and compost fertilizers that are commonly used for the agricultural purposes. Common sources of MPs in the soil include disintegration or fragmentation of the plastic waste in the landfills, use of sewage sludge as a fertilizer, car tire debris, flooding of wastewater, and atmospheric deposition. MPs can also act as a carrier for the migration of various pollutants and, thus, affect the soil ecosystem [40]. A study was conducted by Scheurer and Bigalke, 2018, in which they found that the concentration of MPs in the soil of 26 floodplain sites in Switzerland was about 55.5 mg/kg [41]. In another study, Liu *et al.*, 2018, investigated the concentration of MPs in the farmland soils collected from 20 vegetable fields in Shanghai, China, and found that the concentration of MPs was approx. 62.50 N/Kg in the deep soils (3–6 cm) [42]. Corradini *et al.*, 2019, have shown that the concentration of MPs in the agricultural fields of Chile applied with sludge was about 0.57–12.9 mg/kg [43]. Zhou *et al.*, 2018, reported that the concentration of MPs in the 120 samples of soil collected from the coastline in Shandong province in China was found to be 1.3–14, 712.5 N/kg [44].

6.4. Air

Due to the small size and low density, MPs can travel easily in the wind and can be observed commonly at the downwind sites in large quantity. The common sources of the MPs in the air are the urban dust, erosion of the synthetic rubber tires, and synthetic textiles. A study was done by Dris *et al.*, 2016, in which they found that the suburban fiber fallout was about 50% of the observed urban fallout, that is, 53 particles/m^2/day as compared to 110 particles/m^2/day and thus they concluded that the fallout of fiber is lower in suburban areas comparatively [45]. In further study, Dris *et al.*, 2017, showed that the concentration of MPs can be detected more in the indoor air, that is, 1–60 fibers/m^3, as compared to outdoor air, that is, 0.3–1.5 fibers/m^3 [46]. The concentration of MPs in indoor air is more because there is more release of particles by the sources inside the house as well as there is lower removal rate of particles by dispersal mechanisms [47]. In one of the studies, it was reported that the mean dispersion rate of the MPs in the air is about 132 particles/m^2/d^1 in the outdoor air of the western protected areas of the USA, whereas in Dongguan, China, it was ranging from 175 particles/m^2/d^1 to 313 particles/m^2/d^1 [48,49].

7. IMPACT OF MPs ON THE ENVIRONMENT

MPs have negative impact on humans and biota. MPs can cause intestinal obstruction, esophagus damage, decreased reproduction, and some biochemical responses such as metabolism disorders and decreased immune response, to soil animals. Moreover, MPs adhered to the outer surface of the animals can directly arrest their mobility [50]. It can also alter the activity of soil enzymes that are useful in regulating soil nutrients such as C, N, and P and as an indicator for evaluating the fertility of soil. MPs that are bigger in size (100 nm–5 mm) can affect the plants by modifying or disrupting the soil structure and fertility or by clogging the seed pores. Various studies have highlighted that MPs can cause damage to the gut of the feeding organisms, reduce metabolism and fertility, and obstruction in the digestive tract [51]. In general, exposure of MPs to human results in particle toxicity, with inflammatory lesions, oxidative stress, and increased uptake and also since the immune system cannot discard the MPs, so it might cause increase risk of neoplasia and chronic inflammation [52]. The detailed impact of MP exposure to soil, plant, aquatic organisms, and humans has been described as under.

7.1. Soil

7.1.1. Soil health

MPs can interact with the multiple properties of soil as these particles can integrate into the soil aggregates and incorporate into the soil clumps with varying degree, that is, loosely in case of fragmented type whereas more tightly in case of linear type [44]. Furthermore, a study was conducted by de Souza Machado *et al.*, 2018, in which he found that the polyester fibers can enhance the water holding capacity and decrease the water-stable aggregation and bulk density; although, no change was observed in the water holding capacity in case of PE and polyacrylic acid [53]. However, contrary to the study of de Souza Machado *et al.*, 2018, another study was done by Zhang *et al.*, 2019, in which he observed that there was no significant change in the bulk density and the water holding capacity of the soil, when treated with the polyester microfiber [54]. Therefore, there are no clear findings that show the effect of particular polymer type on the health of the soil. Moreover, MPs can also alter the water retention and permeability of soil which further affects the water evaporation, for example, Wan *et al.*, 2019, conducted a study in which he observed that the addition of MPs can enhance desiccation cracking and water evaporation in two clay soils [55].

Huang *et al.*, 2019, demonstrated that the MPs have significant effects on the activity of various soil enzymes such as urease, phenol oxidase, catalase activities, and fluorescein diacetate hydrolase that can cause short-term effects on soil quality [56]. In addition, for extrapolating the soil carbon storage, soil bulk density is an important parameter and the presence of MPs can lead to misestimation of soil carbon storage. Liu *et al.*, 2017, in a study, demonstrated that 30 days exposure of higher concentration of MPs (28% w/w) to the soil can significantly enhance the dissolved organic matter (DOM) and further allow the release of soil nutrients such as dissolved organic nitrogen, dissolved organic carbon, and dissolved organic phosphorus. However, when the concentration of MPs was reduced (7% w/w), it showed slow accumulation of DOM and also the effects of MPs during the initial 7 days and the concentration of soil nutrients did not also increase until the 14–30 days. Therefore, the exposure time as well as the concentration of MPs have significant effects on the soil quality [57]. Besides that, various studies have also highlighted that the addition of MPs can promote the accumulation of high MW humic-like material which improves the quality of the soil as this material can enhance the soil stability, nutrient availability, and water holding capacity [58]. However, whether the MPs have positive or negative impacts on the soil, this field still need more in-depth research.

7.1.2. Soil microorganisms

The impact of MPs on the soil microorganisms remains largely unexplored. Changes in the soil properties such as soil porosity and soil moisture could change the relative distribution of the aerobic and anaerobic microorganisms due to the alteration in the flow of oxygen caused by the addition of MPs [53,54]. Liu *et al.*, 2017, reported that PP particles (7% and 28%) have positive impact on the activity of soil microorganisms while de Souza Machado *et al.*, 2018, have reported that polymers such as polyester (0.05–0.4%), polyacrylic (0.05–0.4%), and PS particles (1 mg/kg) have negative impact on it [52,53]. Moreover, MPs can affect the transport and deposition of soil microorganisms, for example, He *et al.*, 2018, found that under the low ionic strength conditions of PS particles, *Escherichia coli* had negligible effect while transporting in the quartz sand, whereas under high ionic strength condition, these particles stimulate the bacterial transport [59]. To investigate how MPs can affect the transport of microorganisms in soil systems, further research is needed. de Souza Machado *et al.*, 2019, and Wang *et al.*, 2020, observed that the presence of MPs in the soil can also affect the properties of soil fungus like root colonization rate of AMF at different degrees [60,61]. Chen *et al.*, 2020, reported that PLA MPs could affect the interaction between the microbial species present in the soil and thus further affect the microbial assisted mineral absorption and nitrogen fixation rates [62]. In general, MPs can cause various effects on properties of soil and thus further effects the soil microorganisms which lead to variation in community, structure and diversity, and evolutionary consequences.

7.1.3. Soil animals

Along with microorganisms, soil animals are also affected by the MPs. Ingestion of MPs by animals is accidental in most of the cases as animals consider MPs as food. These ingested MPs can then cause false satiation, which leads to reduction in carbon biomass ingestion that further leads to decreased growth, energy depletion, and, in some cases, death. Song *et al.*, 2019, investigated the toxic effects of PET fiber on snail (*Achatina fulica*) by exposing it to MPs contaminated soil at a concentration of 0.014–0.71 g/kg for 28 days and observed that these fibers could reduce the food intake and excretion, influence oxidative stress, and induce villi damages in the walls of GIT and other adverse effects on snails [63]. Cao *et al.*, 2017, suggested that the exposure of MPs at a concentration of 1% and 2% (w/w) can inhibit the growth of earthworms and further cause lethal effects [64]. Moreover, Jiang *et al.*, 2020, reported that the presence of PS particles could induce DNA damage in the earthworms (*Eisenia fetida*) [65]. Results of Lu *et al.*, 2018, reported that the exposure of mice to MPs can cause hepatic lipid metabolism disorder, decrease the mRNA expression of certain genes that are responsible for synthesis of lipogenesis and hepatic triglyceride in the liver and epididymal fat [66]. Moreover, the consumption of MPs can also lead to disruption of gut microbial community, cause dysbiosis, and significantly affect the diversity and richness of intestinal microbiota. Wang *et al.*, 2019, found that exposure of PE or PS particles at a concentration of 20% w/w can affect the enzymatic activity of earthworms (*E. fetida*), whereas these polymers at a low concentration (10% w/w) had no significant effect on the enzymes [67].

In addition, MPs can also accumulate pollutants from the environment which can act as a potential vector to increase the exposure of pollutants to the animals. Several studies have been conducted, but they all got different results. For example, Hodson *et al.*, 2017, found that comparative to the soil, more amount of zinc was desorbed in the synthetic earthworm guts from the MPs that suggest that the absorption of MPs could increase the bioavailability of zinc [68]. Meanwhile, two studies highlighted that the accumulation of As(V), PCBs, and PAHs was reduced in the gut and body tissues of earthworms in the presence of MPs [67,69]. These contrary results suggested that further in-depth research is needed.

7.2. Plants

On exposure to MPs due to plastic mulching, organic manures, and sewage sludge as fertilizer, the plants that are grown in it get subjected to MPs. Qi *et al.*, 2018, performed a study on wheat plant (*Triticum aestivum*) and found that both the vegetative and the reproductive growth of the plant were affected in the presence of the LDPE MPs (1% w/w) [Table 2] [70]. Jiang *et al.*, 2019, reported that in hydroponic *Vicia faba*, a PS MPs could cause growth inhibition, genotoxic and oxidative damage, reduce biomass, block cell walls pore that transports nutrients in the roots, and reduce catalase enzyme activity [71]. In another study, Wang *et al.*, 2020, performed an experiment on Maize (*Zea mays*) plants and found that PLA caused reduction in chlorophyll content and maize biomass and stronger phytotoxicity and PLA along with PE caused alteration in AMF community diversity and structure and increase the pH and Cd concentration in the soil [61]. PVC is found to be the most toxic MPs for the Garden cress (*Lepidium sativum*) when exposed at a concentration of 0.02% (w/w) for 21 days [72]. Boots *et al.*, 2019, studied the exposure of perennial ryegrass (*Lolium perenne*) to biodegradable PLA and virgin HDPE MP clothing fibers and observed that there was a reduction in biomass and shoot height and also fewer seeds were geminated after the exposure [73]. However,

Table 2: Impacts of MPs on various organisms.

Sample type	Details of MPs	Duration of exposure	Parameters	Observations	References
Dunaliella tertiolecta, Chlorella vulgaris	PS MPs (0.05–6 μm)	72 h	Photosynthesis and growth	• No change in algal growth. • Reduction in photosynthesis (2.5–45%)	[87]
Skeletonema costatum (Diatom)	PVC MPs (1 μm)	96 h	Growth inhibition	• 39.7% growth inhibition • Significant aggregation and absorption	[77]
Hydra attenuata	PE flakes	30 and 60 min	Uptake and morphology	• Effective ingestion of PE MPs. • Changes in morphology but not leads to mortality	[88]
Daphnia magna	PE MPs (1–100 μm)	96 h	Uptake and immobilization	• PE particles were ingested and cause immobilization • EC_{50} value for 1 μm MPs is 57.43 mg/L	[89]
Caenorhabditis elegans	PE, PVC, PS, PA, and PP	2 d	Survival, reproduction, and body length	• Reduction in survival rate • Reproduction impairment • Decreased body length	[90]
Danio rerio (zebrafish)	PE microbeads (19–107 μm)	4–96 h	Uptake and localization	• Significant reduction in uptake of metal after polyethylene beads exposure • Altered bioavailability and uptake of metal contaminant	[91]
Danio rerio (zebrafish)	PA, PE, PP, PVC, and PS (0.001–10.0 mg/l)	10 d	Uptake and mortality	• No or low mortality after exposure to microplastics. • Intestinal damage including cracking of villi and splitting	[90]
Sparus aurata (Gilthead seabream)	PVC and PE particles (40–150 μm)	1 and 24 h	Cell viability, immune parameters, and expression profiles of inflammation related genes	• No changes in cell viability • Significant effects on immune parameters such as reduced phagocytosis and enhanced respiratory burst • Unregulated expression of nrf2 gene.	[92]
Humans	PS MPs particles (5 μm and 20 μm)	-	Inflammation	• Induced inflammation in the liver. • Adverse effects on neurotransmission.	[93]
Humans	MPs (26–130 MPs/d)	-	Respiratory and intestinal responses	• Respiratory symptoms like dyspnea • Intestinal inflammatory responses	[94]
Triticum aestivum (wheat plant)	Low-density polyethylene	-	Vegetative and reproductive growth	• Both the parameters were significantly affected.	[70]
Zea mays (maize)	PE and PLA	-	Biomass and chlorophyll content	• Reduced biomass and chlorophyll content • Both PLA and PE together caused alteration in AMF community structure and diversity.	[61]

MPS: Microplastics, PS: Polystyrene, PE: Polyethylene, PVC: Polyvinyl chloride, PA: Polyamides, PP: Polypropylene

recent studies relatively focused on effects of MPs on smaller plants such as wheat (*T. aestivum*), cress (*L. sativum*), and spring onion (*Allium fistulosm*) [60,70,72]. Therefore, there is a need to conduct more research to understand the impacts of MPs on higher plants, as the concept is still very unclear.

7.3. Aquatic Organisms

Recent researches on the impact of MPs mainly focus on the marine and freshwater organisms. For instance, copepod (*Centropages typicus*), the marine jacopever (*Sebastes schlegelii*), the diving beetle (*Cybister japonicus*), and the crab (*Carcinus maenas*) when exposed to the MPs experienced reduction in the ingestion rate, assimilation efficiency, feeding capacity, and swimming speed. Moreover, on aquatic organisms, MP particles have direct mechanical effects through entanglement and swallowing and these mechanisms wear and tear on the digestive tract of the organisms and thus reduce their food intake capacity and eventually lead to death due to starvation. In 2015, around 690 species were affected by the marine plastic pollution, out of which at least 10% of the species ingested MPs [17]. Furthermore, some species are able to egest the MPs rapidly, whereas other might be unable to do so and thus MPs retain and accumulate in their system. For example, a large amount of microbeads was egested by tadpoles of *Xenopus tropicalis* after they were transferred to clean water with having 95% depuration rate after 6 days [74]. In case of zebrafish (*Danio rerio*), PS microbeads can cause inflammation, oxidative stress, accumulation of lipid in the liver, and accumulation of the microbeads in the liver, gut, and gills [75].

MPs can also impact small-sized planktons due to their small size by acting as substitute of nutrients that are required by planktons and thus resulting in loss of energy and eventually leading to death of the organism. Other studies have highlighted the negative impact of MPs on microalgae including reduction in growth rate, photosynthetic activity, and chlorophyll content [76]. Furthermore, Zhang *et al.*, 2017, observed that the MPs can embed onto the algal cell wall and can cause physical damage [Table 2] [77]. In addition, MPs can affect the organisms at molecular level also, by altering their genes, for example, in case of *Dicentrarchus labrax* and *Mytilus galloprovincialis*, MPs were found to alter the expression of genes that are responsible for biotransformation, DNA repair, immunity, stress response, and lipid metabolism signaling pathways [78]. Furthermore, toxicological effects are caused by additives in MPs as they enter into the organisms along with the MPs and then during desorption process, they are released and cause carcinogenic, endocrine-disruptive, or mutagenic effects in the aquatic organisms [76]. For example, MPs along with pyrene can inhibit the enzymatic activity of acetylcholinesterase, responsible for the neuromuscular and neuronal transmissions, in the goby fish [79]. Oehlmann *et al.*, 2009, demonstrated that the presence of BPA and phthalate can cause genetic aberrations and impair the development of amphibians and crustaceans [80]. Further exploration of metabolism mechanism and effect mechanism of MPs still require more investigation.

7.4. Human Health

Due to the omnipresence of MPs in the environment, its exposure to humans is completely unavoidable. Daily diet of humans consists of various food items and drinks, including sea salt, beer, honey and sugar, seafood, and drinking water that are contaminated with MPs. They ingest approximately 4000 MPs from drinking water and 11,000 MPs from the shellfish every year [40]. Humans are mainly exposed to the MPs through three different routes: Inhalation, ingestion, and dermal exposure. The MPs that are inhaled by humans mainly originates from the sources including urban dust, rubber tyres, and synthetic textiles, while in case of ingestion, MPs contaminated seafoods and other food items and drinking water are the main sources [81]. Although in case of dermal exposure, it is not possible for the MPs to pass through the skin membrane as it is too fine for the particles to pass through it, but it can enter through other possible routes such as sweat glands, open wounds, or hair follicles [82]. All these three pathways' account for the exposure of the MPs to the humans, but dermal exposure of the MPs is still rarely reported to have adverse effects on humans, as only particles having size less than 100 nm can cross the dermal barrier.

As per Catarino *et al.*, 2017, MPs inhalation from airborne household's fibers that fall into our meals is more as compared to the consumption of contaminated mussels [83]. In the study conducted by Prata, 2018, they reported that inhalation of MPs at a concentration of around 26–130 MPs/d can cause respiratory problems like dyspnea and can also induce other inflammatory responses, mainly in case of industrial workers that are exposed to MPs for longer period of time [Table 2] [84]. Phthalate esters can potentially cause harmful effects to humans on exposure including abnormal sex development and birth defects [85]. Many studies have also shown that the BPA that comes out from PC plastics can also lead to alternation in liver functions, changes in development of offspring in the pregnant women's womb, reproductive system, insulin resistance, and brain function [86]. Other researches have shown that the chemical compounds that are present in the plastic or are adsorbed on the MPs can become mutagenic and carcinogenic on their exposure [81]. To understand the risk of MPs to humans, further studies are needed to be conducted.

8. STRATEGIES TO CONTROL MPS POLLUTION

MPs pollution is considered as a planetary boundary threat, as it is irreversible, less degradable and can disrupt various environmental process either through altering their physiochemical properties or by possessing negative impacts on the ecosystem. For controlling this pollution, many clean-up activities have been proposed that include mitigation strategies as well as tools for creating awareness among citizens [94]. Many regions have implemented regulations to forbid the production and use of primary MPs as well as limits or forbid the use of single-use MPs, such as water bottles and carry bags. However, to control the impacts of secondary MPs, currently, there are no established regulations. In 2015, the US Congress has passed the national legislation to control the microbeads plastics in the US. Various non-governmental organizations have also proposed plans to evaluate the level of MPs pollution and their impacts and to further enhance the awareness among individuals.

Other studies have also aimed to reduce the use of single-use plastics at regional, national, and individual level. It has been reported that single bag plastic interventions have reduced the use of plastics between 33% and 96% which helps in reducing marine pollution caused by single-use plastics [95]. The US and France have become the first and second country, respectively, who banned the use of microbeads from the rinse-off cosmetic products with the Microbead-Free Waters Act [96]. In 2018, the ocean plastic charter was adopted by the five member nations of the G7, that is, Canada, Germany, France, Italy, and the UK, which includes enhancing recycling of plastic products by at least 50% by 2030, reuse and recycling of at least 55% of plastics packaging by 2030 and to recover all the plastics (100%) by 2040 and to develop research and technologies that are related to removal of plastics and MPs from sewage sludge and wastewater.

The use of MPs can also be reduced using alternative (e.g., glass) or biodegradable material, by improving the design of the product so that less amount of plastic is used for manufacturing or by limiting the use of number of polymers, additives, and mixtures [97]. At present, 6 Rs strategies, that is, reuse, recycle, redesign, remanufacture, recover, and reduce, are being very popular in our society to reduce the MPs pollution and in cases where this strategy cannot be implemented, biological materials such as bioplastics or plant-based plastics as a substitute are beneficial [98]. Another strategy is the extended producer responsibility, that is, the public policy which makes manufacturers legally and financially responsible to reduce the environmental impacts of their product throughout its production. Several nations including Germany, Denmark, Austria, and Sweden, have banned the practice of landfilling of MPs, which lead to massive increase in the recovery of plastic waste. Recently, biodegradable cellulose microbeads have been invented that could be used as an alternative of plastic microbeads in various applications [99].

Microorganisms, such as fungi, bacteria, and mealworms, can also be used for biodegradation of plastic polymer and they provide environment-friendly action plan for the management of MPs pollution without any negative effects. For example, Bombelli *et al.*, 2017, demonstrated the fast biodegradation of PE polymer by the larvae of the wax moth *Galleria mellonella* [100]. Furthermore, clean-up of plastic pollution from costal and ocean regions is needed to control the marine pollution. Ban of plastic bags could also be an effective strategy to mitigate the MPs and plastic pollution. Spreading awareness about MPs pollution and impacts among universities, schools, and organizations by creating campaigns and educating them about 4 Rs (reject, reuse, recycle, and reduce) of plastics could also be a long-term strategy to reduce the MPs pollution. All the strategies discussed can be used to control the MPs pollution and its impact on environment.

9. CONCLUSION

MP pollution has drastically increased in recent years due to the urbanization, industrialization, and population expansion creating negative impacts globally. Because of MPs contamination in air, water, and soil, most of the organisms and humans are being affected having prolonged impacts. Mitigation strategies to control MP pollution and restore the economic sustainability of the environment need to be explored. Eco-friendly remediation measures to eliminate MPs from environment also need to be utilized for enhancing the habitat of aquatic species, soil organisms, plants, soil structure, air, and water. Furthermore, the use of biodegradable plastics should be practiced to lessen the MP contaminants in the environment.

10. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

11. FUNDING

There is no funding to report.

12. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

13. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

14. DATA AVAILABILITY

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

15. PUBLISHER'S NOTE

This journal remains neutral with regard to jurisdictional claims in published institutional affiliation.

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How to cite this article:
Saini A, Sharma JG. Emerging microplastic contamination in ecosystem: An urge for environmental sustainability. J App Biol Biotech. 2022;10(5):66-75. DOI: 10.7324/JABB.2022.100508