Microplastic Pollution: A Review of Sources, Environmental Fate, Ecotoxicological Impacts, and Mitigation Strategies

Qi Zhou

Department of Biology, Shenzhen MSU-BIT University, Jinan, China

1336606418@qq.com

Abstract. The term 'microplastics' was formally introduced in 2004. Due to the widespread use of plastics and their subsequent mismanagement, microplastics have become ubiquitous in China and globally, posing significant threats to ecosystems. Substantial research efforts have yielded critical breakthroughs in understanding and addressing microplastic pollution. This paper systematically analyzes the sources of microplastics, migration patterns, toxic mechanisms, and corresponding environmental governance measures. In terms of the sources of microplastics, the plastic sources in different regions are analyzed, and the plastic components in microplastic-polluted objects are also classified. The migration patterns of microplastics are divided into two categories: biological and non-biological. Non-biological migration includes climate, rainfall, rivers, wind-driven mechanical transport, and biological migration includes food web migration and biological activity carrying. The ecological toxicity of microplastics encompasses environmental pollution, microplastics' direct impact on organisms, including microplastics on plants and humans, and microplastic governance.

Keywords: Microplastics, pollutants, environmental governance.

1. Introduction

Microplastics refer to plastic particles with a diameter of less than 5 millimeters, which can be divided into primary and secondary microplastics according to their sources. Primary microplastics are plastics that are directly produced as tiny particles and put into use, such as exfoliating microbeads in personal care products, fibers shed from textiles, rubber particles containing plastic components generated by tire friction, etc. Secondary microplastics, on the other hand, originate from plastic products that undergo a complex of physical and chemical degradation in the natural environment [1]. Microplastic pollution represents one of the most critical global environmental challenges of the 21st century. Since the formal introduction of the term in 2004, studies have confirmed the pervasiveness of microplastics in nearly all ecosystems—from oceans and freshwater to soil and the atmosphere—with further migration through food chains into human blood, placenta, and multiple organs[2]. Studies have documented that the microplastic abundance in the arable fields of the black soil area in Northeast China is 198.32 ~1002.61 pieces/kg, of which the microplastic abundance with agricultural film coverage is 1.69 times that without agricultural film coverage [3].

Microscopic plastic fragments and fibers are widespread in the oceans and have accumulated in pelagic and sedimentary habitats. The fragments appear to have resulted from the degradation of larger items. Marine organisms ingest plastics of this size. This demonstrates that microscopic plastics are common in sedimentary habitats [4].

The main categories of microplastic ingredients are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and nylon (PA). Nine polymers were conclusively identified: acrylic, alkyd, poly (ethylene: propylene), polyamide (nylon), polyester, polyethylene, polymethacrylate, polypropylene, and polyvinyl-alcohol [4].

The main components of the Sources of microplastics in arid regions are the use of agricultural plastic film, the abandonment of plastic bottles by tourists, plastics produced by industrial production, and microplastics introduced by atmospheric deposition [5]: ecological security and human health. Human health is facing a dual threat. While current research has advanced our understanding of Sources (e.g., agricultural film and tire abrasion contributing >50% of urban emissions) and migration mechanisms (biological/non-biological pathways), significant gaps remain. Research and development of targeted inhibitors for the physiological toxicity of microplastics to the human body have not yet succeeded. The governance cost of microplastics is also ambiguous. This review aims to synthesize the full lifecycle of microplastic pollution to inform cross-media integrated governance solutions.

2. Microplastics Sources

With the acceleration of urbanization, many primary microplastics enter the sewage treatment plants through domestic sewage. Although sewage treatment plants have a high removal rate of microplastics, the high effluent means that a large amount of microplastics will be discharged into the aquatic environment through effluent [6]. Microplastics generated from plastic film mulch, organic fertilizers, sludge returning to the field, irrigation, etc., in agricultural activities can additionally enter the artificial wetland system through various pathways. Plastic film mulch is widely used in cold and arid areas of the world to maintain suitable temperatures and increase crop yields. In places with recycling rates, they fragment into microplastics that enter the Soil environment [6]. Some cleaning agents contain abrasive plastic fragments. Hence, there is considerable potential for large-scale accumulation of microscopic plastic debris [4]. Daily waste and dust from tyres, asphalt, and road marking paints are considered the primary Sources of microplastics in surface runoff. In Europe, more than 50% of the microplastics from tyre wear, road marking paints, etc. are released into urban water environments each year. In the meantime, microplastics from urban dust resuspension, wear of synthetic rubber tyres, and from synthetic textiles, construction activities, waste incineration, etc., can enter the artificial wetland through atmospheric deposition and surface runoff [6].

3. Migration and Transformation of Microplastics

Anthropogenic activity patterns and regional environmental characteristics influence the migration pathways of microplastics. The paths of natural migration of microplastics include biological migration non-biological migration, where biological migration involves the spread of microplastics through the food web by organisms consuming animals and plants that contain microplastics, as well as the of plastic products by organisms for specific reasons (e.g. plastic bags hooked on the fins of fish), and non-biological migration mostly occurs due to extreme conditions (e.g. heavy rain, sandstorms, tornadoes). Anthropogenic activities, such as tourism, composting, and land use, directly generate microplastics and exacerbate pollution severity and complexity by accelerating the degradation of plastics and the emission of toxic additives in plastics [3].

4. Ecotoxicology of Microplastics

4.1 The impact of microplastics on plants

Agricultural film mulch is widely used in agricultural production because of its good water and heat preservation characteristics. Still, the film's rough surface facilitates aggregation of large microplastics on the root hairs and cell apertures under the action of root exudates. Microplastics directly impact root morphology, affecting root growth and development and the absorption of nutrients by reducing root length, surface area, and root. Microplastics with small diameters are absorbed by the root system and enter the plant body through transpiration, causing damage to the plant's organs. At the same time, it produces oxidative stress, metabolizes to produce active oxygen, induces and expresses genes related to photosynthesis, inhibits photosynthetic synthesis, and ultimately leads to the synthesis of matter. [7,8]

Microplastics have a variety of impacts on the soil ecosystem. They can change the soil's physical properties, increase the soil's bulk density, and destroy the structure of soil aggregates; they can form channels for the movement of soil moisture, accelerate evaporation, and affect the distribution of moisture and aeration. MPs impede nutrient release and affect the availability of soil mineral nutrients, weakening soil fertility, and affecting the content of Soil carbon, nitrogen, phosphorus, potassium, and nutrients by changing the expression of related genes, enzyme activity, and microbial community composition [8]. The continuous exposure to microplastics can additionally be absorbed into the intestines by protozoa such as earthworms, affecting the absorption and utilization of earthworms (affecting soil organisms) for surface litter and humus.

In addition, due to microplastics' special surface structure, large specific surface area, and strong adsorption capacity, they can become carriers for accumulating other organic pollutants such as heavy metals, pesticides, and antibiotics. This increases the toxicity of contaminants, migrates and releases them to deeper Soil, and even pollutes groundwater [9].

4.2 Toxicity on the Human Body

Since Leslie detected microplastics in human blood in 2022, microplastics have been discovered in multiple organs, such as the lungs and heart [10–12]. Microplastics were also found in the placenta, indicating that they might be transported to the fetus through the mother [13]. Microplastics can absorb, release, and transport chemical substances [4].

The routes of microplastics entering the human body are inhalation and ingestion. As an essential step for food entering the human body, the digestive system is one of the first to come into contact with microplastics. Microplastics in food enter the organs such as the pharynx, esophagus, stomach, and intestines through the mouth. The small intestine, as an essential digestive and absorptive organ, plays a vital role in the absorption of microplastics. Studies have shown that the absorption of microplastics is mainly achieved through the endocytosis translocation of intestinal epithelial cells, and it is additionally possible to take microplastic particles through the phagocytosis of M cells and receptor-mediated endocytosis. It has been reported that microplastics smaller than 10 μm can be transferred from the intestines of mammals to the lymph and circulatory systems, causing systemic exposure. Ultimately, about 94 microplastics in the digestive tract are excreted through feces, urine, and other pathways.

The respiratory system is another pathway for microplastics to enter the human body. When air containing microplastic particles is inhaled, these particles deposit in the respiratory tract. Microplastics deposit in the upper respiratory tract, such as the nasal cavity and pharynx. In contrast, smaller microplastics (less than 5 μm), especially nano-microplastics with a diameter of less than 100 nm, can deeply penetrate the respiratory tract and deposit in the lungs, or even penetrate the alveolar barrier and enter the circulatory system, and subsequently reach various tissues and organs [14].

Nanoplastics can internalize in neurons through clathrin-dependent endocytosis, causing a mild lysosomal impairment that slows the degradation of aggregated α-synuclein. In mice, nanoplastics combine with α-synuclein fibrils to exacerbate the spread of α-synuclein pathology across interconnected vulnerable brain regions, including the strong induction of α-synuclein inclusions in dopaminergic neurons in the substantia nigra. These results highlight a potential link for further exploration between nanoplastic pollution and α-synuclein aggregation associated with Parkinson's disease and related dementias [15].

5. Microplastics Management

5.1 Microplastics Governance Measures

Removing microplastics by constructed wetlands involves a collaboration of several processes, including matrix retention and adsorption, biofilm retention, plant interception, and microbial degradation [6].

5.1.1 Physical Method

Physical methods mainly remove microplastics from water bodies through bodily actions, and standard methods include adsorption and magnetic separation. The adsorption technology uses the properties of adsorbents to adsorb microplastics in water. Sand substrates play a pivotal role in controlling microplastic pollution in constructed wetlands, which can effectively remove microplastics through filtration, adsorption, and entangling effects [16].

Moreover, biochar can also be used as a substrate to improve the removal capacity of microplastics. In addition, the removal efficiency of microplastics from water using date residue-derived biochar can reach above 98% for nylon and polyethylene. The surface area of biochar and many micropores on the surface show a better adsorption effect on microplastics in water [17].

Metal-modified biochar (e.g., Mg/Zn-modified biochar) was more effective in removing microplastics than unmodified biochar [18]. While these adsorbents exhibit high efficiency, their preparation costs and regeneration requirements present practical limitations.

5.1.2 Biological Method

Planting plants in places where microplastic pollution is severe can effectively intercept and retain microplastics. Roots can intercept larger microplastics, stems, and leaves, while the Soil matrix can capture smaller plastic particles [19]. Meanwhile, microbial degradation can additionally manage microplastic pollution. The central mechanisms of microplastic degradation are bacteria, fungi, and algae breaking down the long polymer chains of microplastics. The depolymerization of microplastics by organisms usually involves hydrolysis [20]. During hydrolysis, microplastics bind to enzymes secreted by bacteria or fungi and are subsequently degraded by organisms into short chains or smaller molecules.

5.1.3 Chemical Method

Chemical methods degrade MPs mainly through chemical reactions, and standard techniques include pyrolysis and advanced oxidation processes. Pyrolysis decomposes MPs chemically at high temperatures. When pyrolysis temperatures reach 450℃, PE and PP MPs in sludge can degrade completely [21].

Pyrolysis technology has a particularly significant effect on the degradation of small-sized microplastics. Still, it has high energy consumption, may produce harmful gases, and needs further optimization. Advanced oxidation processes (AOPs) refer to the degradation of microplastics by generating strong oxidizing free radicals (such as hydroxyl radicals ·OH, sulfate radicals $SO_4^{-}\cdot$). They can attack the chemical bonds in the molecules of MPs, leading to the breakage of their molecular chains, a decrease in molecular weight, and eventually degrade them into inorganic substances such as carbon dioxide and water. AOPs include Fenton reaction, ozone oxidation, catalytic oxidation, peroxysulfate and peroxymonosulfate activation, sonochemical oxidation, and other methods. [22-24].

5.2 Policies and Public Awareness for Environmental Protection

Reducing plastic pollution from the source requires enhancing public awareness of the issue and promoting knowledge about its prevention and control. In daily life, most people lack understanding of microplastics and are unaware of their sources and potential environmental and health hazards. Urgent measures are required to enhance public risk perception through education and the dissemination of ecological knowledge. Disseminating this knowledge to elevate public consciousness and foster sustainable behaviors is imperative. In this way, the generation of microplastics can be reduced from the source, which has significant practical significance for the governance of the marine environment.

China’s National Development and Reform Commission and Ministry of Ecology and Environment announced on the 19th the “Opinions on Further Strengthening the Governance of Plastic Pollution”, banning the production and sale of ultra-thin plastic shopping bags with a thickness of less than 0.025mm and polyethylene agricultural film with a thickness of less than 0.01. The production of plastic products from medical waste is also prohibited. The import of waste plastics is also completely banned. By the end of 2020, the production and disposal of foam plastic tableware and disposable plastic swabs will be prohibited; daily chemical products containing plastic microbeads will be banned. By the end of 222, the sale of daily chemical products containing plastic microbeads will be restricted. The EU' s "Cosmetics Ban" has already completely banned the sale of products containing microbeads.

Management of agricultural film and alternative technology, promoting fully biodegradable agricultural film instead of so-called biodegradable plastics, and establishing a mechanism for recycling agricultural film. Tire wear accounts for more than 50% of urban microplastics, which can be reduced by adding silica dioxide to tire materials or launching new material tires.

6. Conclusion

Microplastic pollution constitutes a global environmental crisis characterized by complex sources permeating soil, aquatic systems, and atmosphere via agricultural mulch, industrial discharges, urban activities, and atmospheric deposition; migration pathways exhibit high diversity, where abiotic processes (climate-driven transport, riverine flow) and biotic processes collectively facilitate cross-media dispersion, while anthropogenic activities exacerbate pollution complexity by accelerating plastic fragmentation and toxic additive release. Source control through legislation against primary MPs, remediation technologies spanning physical methods (substrate adsorption in constructed wetlands, >98% removal efficiency of nylon/PE by biochar), biological approaches (plant interception, microbial enzymatic hydrolysis), and chemical processes (pyrolysis at 450° C for PE/PP degradation, AOPs radical mineralization), management innovations requiring fully biodegradable mulch and tire material modification (silica additives), alongside public environmental education to drive behavioral change.

To develop corresponding targeted inhibitors against the physiological toxicity of microplastics to humans. Microplastic research constitutes a resource-intensive endeavor that requires the establishment of models to quantify the economic benefits of different governance programs and the extent to which they effectively protect the environment.

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