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Review Article

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India on the Verge of a Microplastic Disaster-The Indestructible and Invisible Pollutant

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Abstract

Tiny fragments of plastic particles termed as Microplastic collectively pose an invisible threat to human health through contamination of air, water, soil, and food. The loading of microplastics in the environment has increased significantly in recent decades due to the dramatic rise in plastic production and use, driven by its affordability, lightweight nature, moisture resistance, tensile strength, and durability. Poor management and inadequate recycling of plastic waste have further exacerbated the concentration of microplastic particles in global water bodies. Microplastics transport heavy metals, pathogens, and pollutants; and support microbial biofilm growth with algae, fungi, and bacteria. They accumulate in human tissues and cells, potentially inducing cardiovascular toxicity through interaction with plasma proteins, leading to heart dysfunction. India's major river systems show microplastic pollution levels exceeding 6,000 particles m-3. The pollutant has moved from these systems to the food chain and even to edible salts. Plastic recycling industries also contribute as a point source of microplastics. Due to lack of adequate control and remediation measures, current mitigative measures for microplastic pollution primarily rely on the 5 R's (*Refuse, Reduce, Reuse, Repurpose,* and *Recycle*) at the stakeholder level.

Keywords: Pollution; Solid Waste; Indian Scenario; Health Impact; Environmental Impact; Control Measure

Introduction

Microplastics pose an invisible threat to human health through air, water, soil and food. Tiny fragments of plastic particles collectively termed as Microplastic, <5 mm in size, have invaded every part of our environment and have increasingly emerged as a severe threat to human health and biodiversity. The loading of microplastics in the environment has increased tremendously in recent decades due to the dramatic increase in production and use of plastics because of their affordability, lightweight nature, resistance to moisture, tensile strength, and extended durability [1]. In addition to this, inappropriate management and inadequate recycling of plastic waste have played a major role in increasing in microplastic particle concentrations more specifically in global water bodies. Microplastics can float on the surface of water due to their small size and high buoyancy, allowing them to be transported over long distances by winds and water currents in the rivers and oceans, and their pollution is identified as a significant ecotoxicological hazard for different aquatic and terrestrial lifeforms [1].

Microplastics in the environment can be broadly divided into two categories. Primary microplastics, which are microbeads that typically occur in cosmetic products, plastic pellets from industrial manufacturing processes, and other synthetic materials used in detergents, paints, medications, diapers, insecticides, and fibers used in synthetic textiles, and

Secondary microplastics, which are shredded micro pieces forming from large plastic waste as a result of weathering processes on exposure to environmental stress. There are five major types of microplastics, namely, fragments, fibers, films, pellets, and foams that can be further categorized into six categories based on their chemical composition. These are polyethylene, polystyrene, polypropylene, polyurethane, polyvinyl chloride, and polyethylene terephthalate.

Recent research across the globe suggests that particles of microplastics have contaminated aquatic and terrestrial ecosystems. In addition, the increased presence of microplastics has now contaminated both indoor and outdoor air, making them more likely to be inhaled. Upon inhalation, microplastics can be transported throughout the body, potentially ending up in various organs, depending on their size, more evidently in human lung tissues [2,3].

Origin and Current Scenario

The term 'Microplastic' was coined by Thompson Richard Charles in 2004 while documenting small-sized plastics in oceans [4]. These particles are primarily the result of increased plastic use and poor waste management practices, which have led to higher levels of microplastic contamination in aquatic and terrestrial environments. In addition to water bodies carrying these tiny particles, dump yards and landfills are also major sources of microplastic pollution in the soil and groundwater. The increase in microplastic pollution is directly linked to the increased use of plastic products in our day-to-day lives. The diverse use of plastic is responsible for the addition of ~350 million metric tonnes of plastic waste globally [5]. Around 90% of this waste is either dumped in landfills or ends up in water bodies like lakes and rivers and eventually reaches the oceans, where due to physical, biological and chemical weathering processes it disintegrates into microplastic particles. Plastic waste found in the dump yards is more prone to extreme UV exposure, high temperatures and chafing. Upon disintegration, the smaller particles are more active and are transported both vertically and horizontally due to mechanical or biological stresses. The vertically mobile microplastic particles end up in groundwater aquifers [6]. Through irrigation, extraction and consumption of groundwater, and plant uptake, these microplastics enter the human body. Microplastics have also entered our food chain through different aquatic food sources [7]. Leachates from dumping and landfill areas contribute an average of 0.34 particles kg^{-1} of agricultural soil to 80 particles l^{-1} of groundwater [8].

Globally, some 200-500 thousand tonnes of microplastics enter our marine ecosystems annually from textiles which contribute 16-35% of the total microplastic pollution due to changing lifestyles towards fast fashion and increasing consumerism [9]. A significant proportion of this originated either from the direct washing of synthetic clothes in water bodies or instrumental washing directly released as wastewater effluent. Wastewater treatment plants can remove a significant concentration of these microplastic particles, but they are not adequate to remove the entire mass arising from textile washing. Almost 300 thousand tonnes of primary microplastic particles and 530 thousand tonnes of secondary microplastic particles are released into the environment annually across the globe [9]. In the last few years, microplastic load in the environment has increased tremendously with their abundance being detected in many ecosystems starting from a few particles to thousands of particles m^{-3}. As per an estimate [10], a total of 24.4 trillion particles of microplastics weighing 10 MT were said to be distributed in the world's oceans. If the current trend of microplastic addition continues, the amount will be doubled by 2030 Isobe [11].

According to a US-based study Cox [12], annual human intake of microplastic ranges from 4,000–52,000 particles from packaged food items annually, while, it increases to 1,21,000 when inhaled microplastic particles are also taken into account. On average, individual intake of microplastic particles can reach up to particles daily, among which children's consumption ranged between 203 and 223 particles.

Health Risks and Biological Impacts

Microplastics act as vectors translocating heavy metals, pathogens, coliforms, different pollutants, and inorganic chemicals, and are good habitats for microbial biofilm growth containing algae, fungi, bacteria, etc. [13]. In marine animals, microplastic ingestion is known to alter the physiology of the gastrointestinal tract, depress the immune system, induce oxidative stress, and cause growth retardation [14]. Exposure to microplastics leads to the accumulation of such particles in human tissues [15]. Exposure to microplastic pollution has also been found fatal for some of the corals such as Scleractinia, a stony coral that shows stress response and suppressed immune system due to microplastics. Microplastics in the soil effectively interfere with the soil-inhabiting biota and modify their functional diversity [16] ultimately impacting the adequate cycling of essential nutrients important for plant growth.

The airborne microplastics accumulate in the respiratory system and are ingested through food in the digestive system, possibly entering the bloodstream, where they undergo bioaccumulation inside the tissues and can potentially interfere with normal body functioning. Once within the human body, microplastic particles can interact with circulating cells, triggering an inflammatory response, and causing genotoxic and cytotoxic effects on immune cells, with increased haemolysis, and adhesion to the endothelium. The accumulation of microplastics in human tissues and cells has the potential to induce cardiovascular toxicity [17], leading to heart dysfunction because of their interaction with plasma proteins. Due to the deposition of plastic fragments into cardiomyocytes, oxidative stress is heightened, and metabolic parameters undergo alteration. Consequently, this scenario can lead to myocardial damage, fibrosis, and impaired electrophysiological values [17]. Studies have reported the evidence and presence of microplastic particles in human mother's milk and placenta [18]. In a study in Rome with breast milk samples from 34 mothers, 75% of them were detected to have microplastic particles in the milk [19]. Studies on biological endpoints like cytotoxicity, immune response, oxidative stress, barrier attributes, and genotoxicity have revealed that even mild doses of microplastic particles (10–20 μg ml^{-1}) cause cytotoxicity and immunological responses in humans [14,20,21].

Global Concern

Global reports have raised alarming concerns about microplastic pollution and their potential entrance into our food chain. Pristine environments like the Southern Ocean and the Antarctic region have also been polluted with microplastics where bacteria colonizing on such particles have been observed [22]. This raises concerns about the fatal impact of translocating antibiotic-resistant genes or bacteria on the fauna of such geographically isolated regions. Floating microplastic particles get trapped and undergo further modifications, and are then available to the grazing species when the ice melts in warmer temperatures. Microplastics have been found in the intestines of Penguins, Seabirds, Fur Seals, Fishes, and Benthos inhabiting the Southern Ocean and the Antarctic region [23-25]. The Antarctic Peninsula has seen an increase in maritime traffic due to the presence of scientific research stations, tourist vessels, fishing vessels, and research vessels. This, along with long-range sources such as the melting of ice containing particles and degraded plastics carried by wind and ocean currents, indicates the increasing presence of microplastics in these remote environments [23,24]. Microplastic particles from these environments as well as from all the aquatic ecosystems have entered the entire food chain of the region through microarthropods, a part of the benthic organisms, and planktons.

The endpoint translocation of microplastic particles into groundwater and underground aquifers has led to an abundance of microplastics in tap and bottled water globally. Bottled water collected from Brazil (47–863 particles l^{-1}), China (165–731 particles l^{-1}), India (32–5,230 particles l^{-1}), Indonesia (133–4,713 particles l^{-1}), Kenya (335 particles l^{-1}), Lebanon (153 particles l^{-1}), Mexico (92–2,267 particles l^{-1}), Thailand (3,526 particles l^{-1}), and the USA (256–5,106 particles l^{-1}), including other sources like amazon.com (74–10,390 particles l^{-1}) belonging to 11 brands have microplastic particles 32–10,390 l^{-1} [26]. The mean concentration of microplastic particles in all these purchase locations is represented in (Figure 1). Among them, the dominant components are, polypropylene (54%), nylon (16%), and polystyrene (11%) having 65% fragmented particles, 14% films, 13% fibers, 5% foams, and 3% pellets. In addition to the outer environment, most of the air-tight indoor environments have also been contaminated with microplastic pollution. Case studies show that the concentration of microplastic particles in indoor environments is 1–60 fibers m^{-3} sometimes exceeding the outdoor environment (0.3–1.5 fibers m^{-3}) [6]. Most of this is from materials used in the indoor environment containing cellulose fibers, acetate cellulose, or keratinous wool; others include synthetic polymers like polypropylene. In a study by Allen, et al. [27], the deposition of microplastics was found at a count of 249 fragments, 73 films, and 44 fibers for every square kilometre of the area of French Pyrenees mountain ranges. From all accounts, the potential of microplastic as a particulate matter pollutant is startling.

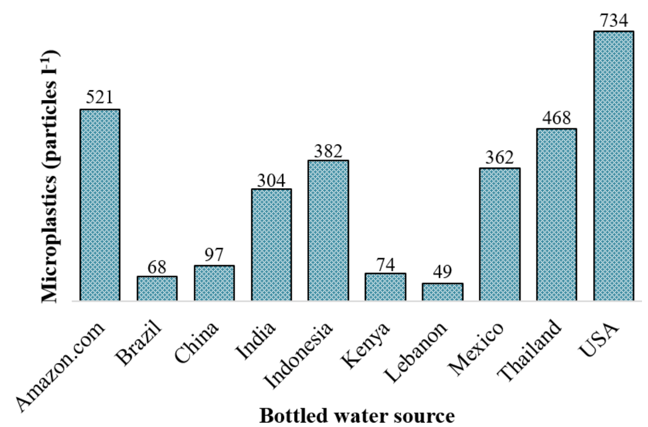

Figure 1: Mean concentration of microplastic particles in bottled water from different purchase locations [26].

Indian Scenario

The production of microplastic is significantly related to the environmental weathering process and the hardness of the plastic. Reports suggest that breakable materials produce more microplastic in comparison to easily stretchable plastic products in the shredding process [28]. Plastic mulching which is widely used in agricultural practices to reduce moisture loss and growth of weeds has been reported to be the prime point source of microplastic pollution [29] in India weighing >4 g kg^{-1} of farm soils, in addition to hoses and packaging materials of agrochemicals in the country. A study conducted in Northeast India found an abundance of microplastics ranging from 4 to 52 particles in the commonly edible and widely marketed fish varieties of Loktak Lake [30], which is the largest floating freshwater lake in Southeast Asia, and a Ramsar Site (463) located in Manipur. One of the major contributing factors to the degradation of the quality of ecosystem services in the lake is the Nambul River, which carries industrial waste from the capital city of the state. Additionally, untreated household discharges, the use of fish drying traps, huts on the *phumdis* (floating islands in the lake), fishing nets and ropes, foam-made fish boxes, and dumped waste from tourism in the area are major anthropogenic factors responsible for the concentration of microplastics in the lake's fish [30]. In India, microplastics have largely been found in marine ecosystems across the southeast, southwest, and western coastlines. Reports show that the abundance of microplastics in coastal sediments is up to 1,150 particles kg^{-1} [31,32] with mass reaching up to 4747.6 mg m^{-2} [33]. Estuaries in Indian marine ecosystems mostly have high concentrations of microplastic particles. Waste from industries, densely populated urban developments in and around watersheds, and surface runoff from dump yards directly contribute to this [32].

India's major river systems, namely the Ganga, Yamuna, Adyar, Kosasthalaiyar, Muthirappuzhayar, Alaknanda, Sabarmati, Brahmaputra, Hooghly, Netravathi, Godavari, etc., have been polluted with microplastics, with concentrations reaching >6,000 particles m^{-3} [34-36]. Among these, the Alaknanda River (2260 particles m^{-3}) has the highest loading of microplastics spatially distributed in the sediment followed by Yamuna (1780 particles m^{-3}), and the least is in the River Muthirappuzhayar (200 particles m^{-3}). Microplastic particles heavily burden the downstream of Indian rivers, accounting for about 50% more than the upper and mid stretches. This is because the river's midstream flows through settlements or urban neighbourhoods [35], which are one of India's major sources of direct and point sources of microplastic pollution. However, concentrations of microplastics in the sediment mass are highest in the Ganga (4319 particles kg^{-1}), followed by Brahmaputra (998 particles kg^{-1}) (Figure 2). The case study of Ganga shows polluted tributaries namely Suswa, Bindal and Rispana carrying microplastic loads ranging from 2,800 – 4,200 l^{-1} floating and 7,200 – 16,400 kg^{-1} of sediment are the major non-point sources of microplastic concentrations in the major Indian rivers [36]. In these three rivers, the dominant microplastic particles are films, pellets, and fibers, indicating the unscientific disposal of sewage water and urban solid wastes, the use of plastic nets, and the decomposition of other plastic products due to natural weathering processes. Components of the pollutant particles are fiber, foam, fragments, and films characterized by polypropylene, high-density polyethylene, low-density polyethylene, ABS, EVA, polystyrene, and nylon [36,37].

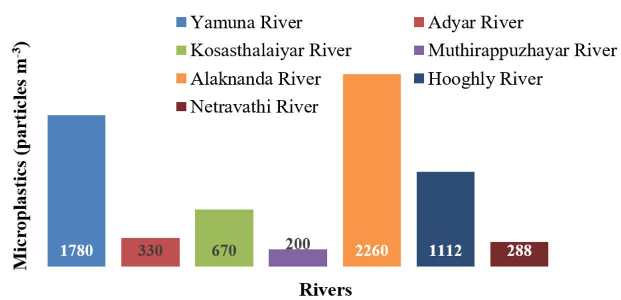

Figure 2a: Average floating microplastic concentration in some of the major Indian Rivers [38-40].

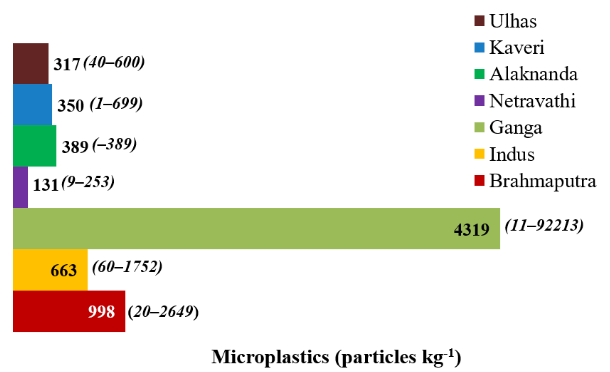

Figure 2b: Average microplastic concentrations in the sediment of some major Indian Rivers. Values within parentheses represent ranges [41-53].

The Indian Himalayan ranges are considered to have pristine ecosystems but are now burdened with microplastic abundance with concentrations ranging from 600–2,500 particles m^{-3} [41]. Reports attribute the high concentration of microplastics in the Jhelum River after municipal solid waste dump sites to contributing factors such as the river's proximity to waste dump yards, wastewater treatment plants, and industrial discharges [41]. The terrestrial ecosystems have also been contaminated with microplastic loadings, whereas coastal areas have the highest concentration (527 particles kg^{-1}) followed by agricultural lands (189 particles kg^{-1}). Indian compost with an average microplastic concentration of 1220 particles kg^{-1} remains the major contributory distributor for increased contamination of microplastic particles (Figure 3). Compost prepared using unsegregated municipal solid waste may be the key source of microplastic contaminants in the soil. According to a Kerala source allocation study, single-use plastic products are responsible for loading 64–77% of microplastics in India. Significant concentrations of heavy metals like lead, cadmium, zinc, copper, and manganese were identified to be associated with the microplastic particles in these composts [42]. One such study showed that the contaminants are dominated by polyethylene, polyvinyl chloride, and polypropylene sourced from unscientific disposal of Municipal Solid Waste across the 167 km stretch of the Jhelum River in Kashmir [41]. In another comprehensive study, microplastics were found piled with 3,800 particles kg^{-1} and 1,19,000 particles m^{-3} of sediment in Indian freshwater ecosystems, which included samples from 12 major rivers and lakes [38]. The pollutant has translocated from these systems to the food chain and even to edible salts. The concentration of microplastics found ranges from 3,515 to 7,240 kg^{-1} of edible salts in India [34] (Figure 4). Alongside, plastic recycling industries are also a point source [43] and contributor of microplastics to the environment [28,44].

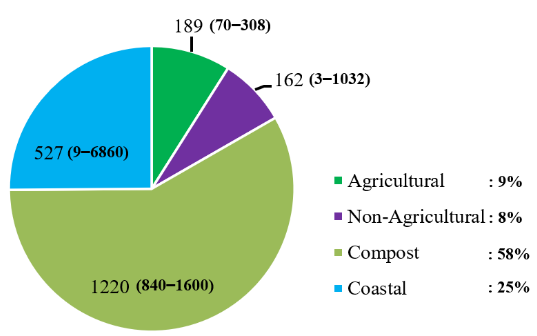

Figure 3: Average concentration of microplastics (particles kg^{-1}) in Indian soils, compost, and coastal sediments. Values within parentheses represent ranges [30,42,45-47].

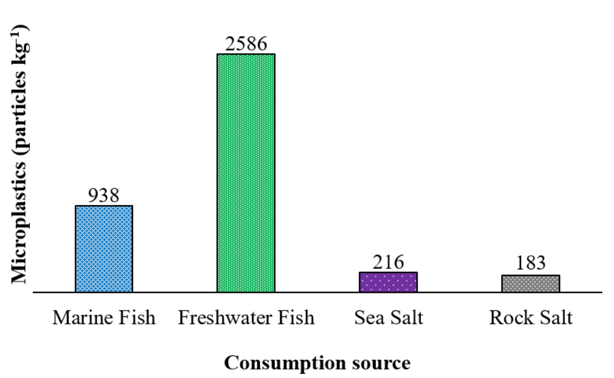

Figure 4: Average source concentration of microplastics in food in India [1,31,47-51].

Limitations, Future Directions, and Concluding Remarks

The status of microplastic pollution across the nation is yet to be explored fully, and their negative impacts lack rigorous establishment. Scientists at the Indian Institute of Science have developed a new hydrogel technology that significantly reduced microplastic particles from the controlled environment [52]. A complex substance has been prepared using: Chitosan, Polyvinyl alcohol, Copper sulfate pentahydrate, Molybdic acid, Phosphoric acid, Ethylenediamine, Terephthalic acid, Hydrochloric acid, Aniline, and Ammonium persulfate. The interpenetrating polymer network of the hydrogel binds with the contaminant particles and effectively degrades them in the presence of UV light. However, its wide application against real-world stresses has not been evaluated. Exceptional care is required while introducing such technology for wider application so as not to generate another issue while resolving one. Besides, no methods are currently available to segregate microplastics from the environment. Current mitigative measures rely only on reducing microplastic pollutants at the source, which depends primarily on the 5 R's *i.e.*, *Refuse*, *Reduce*, *Reuse*, *Repurpose* and *Recycle*. More innovative research is required to devise advanced techniques capable of effectively mitigating microplastic pollution in the environment while concurrently addressing its adverse effects on human health and ecosystems.

A huge proportion of the Indian populace is yet unaware of the current and projected impact of the microplastic disaster. Therefore, generating awareness among the people is the foremost requirement of the mitigative measures to reduce waste-derived microplastic generation at the source. Communities and stakeholders can cumulatively help in reducing the devastating impacts of microplastic pollution. Different government and non-governmental agencies/ institutions can collaborate with communities to minimise waste generation and divert, repurpose or recycle the generated waste. Industrial participation through sustainable product design, use of eco-friendly materials, minimal packaging, innovative technologies, rigorously adopting and implementing environment-friendly targets, and most importantly increasing product durability will be crucial in averting the disaster ahead.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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