Microplastics from Soil and Groundwater to Human Body: A Review

Bharat Kumar Rajabattula[1*], G Appa Rao[1], Abhinash Marukurti[2]

[1]**Department of Geosciences, Adikavi Nannaya University, Rajamahendravaram, Andhra Pradesh, India -533296.**
[2]**School of Life and Health Sciences, Adikavi Nannaya University, Rajamahendravaram, Andhra Pradesh, India -533296.**

Corresponding author:
rbk9393@gmail.com

Abstract. Microplastics (MPs) are plastic particles smaller than 5 mm in diameter, emerged as a significant environmental contaminant, posing serious threats to human health, groundwater, and soil ecosystems. MPs get enter in to the environment through various process, such as the disintegration of bigger plastic waste and the dispersal of fibers from synthetic materials. MPs can alter soil properties, potentially reducing agricultural productivity and biodiversity. In groundwater, MPs facilitate the mobility of trace elements, which can contaminate drinking water systems, thereby increasing the risk of adverse human health effects. Inhalation or ingestion of MPs could result in toxicological outcomes thus oxidative stress, inflammation, and the accumulation of harmful chemicals or pathogens. However, the complete magnitude of microplastic related hazards to human health remains poorly understood, pointing out the necessity of urgent research to assess exposure levels, the processes of toxicity, and the long-term consequences. This review highlights the origins, transport, and environmental contamination of microplastics, together with the potential consequences on soil, groundwater ecosystems, and human health.

Keywords: Microplastics, Soil, Groundwater, Human consequence.

R. K. Ramachandra et al. (eds.), *Proceedings of the International Conference on Bio-Based Environment for Sustainable Territory (IC-BEST 2024)*, Advances in Biological Sciences Research 44,
https://doi.org/10.2991/978-94-6463-648-2_23

1. Introduction:

The first report on Micro plastics (MPs) distribution was published by *Thompson et al., (2004),* and defined as plastic debris smaller than 5 mm are microplastics. MPs are omnipresent in all accounts of the terrestrial and fluvial ecosystems [1] and an quintessential example of unnatural waste and earth pollution [2]. Besides the advantages of plastic products, the rapid increase in their production causing adverse impacts on the environment, over the past few decades [3], [4]. It is estimated that almost 12 billion metric tons of plastic trash have accumulated in the environment as a result of extensive plastic manufacture and incorrect use [5]. Approximately 9% of plastics recycled by different process and the remaining 91% plastics accumulate into the earth environment since many decades [6].According to their point of origin, MPs are separated into two types; Primary and secondary MPs. The primary originates from textiles, medicines, personal care products etc. while the secondary derives from the disintegration of MPs due to physical, chemical, and biological process [2], [7]. The most frequently detected micro-plastics are made up with polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinylchloride (PVC), polyethylene terephthalate (PET) [8].

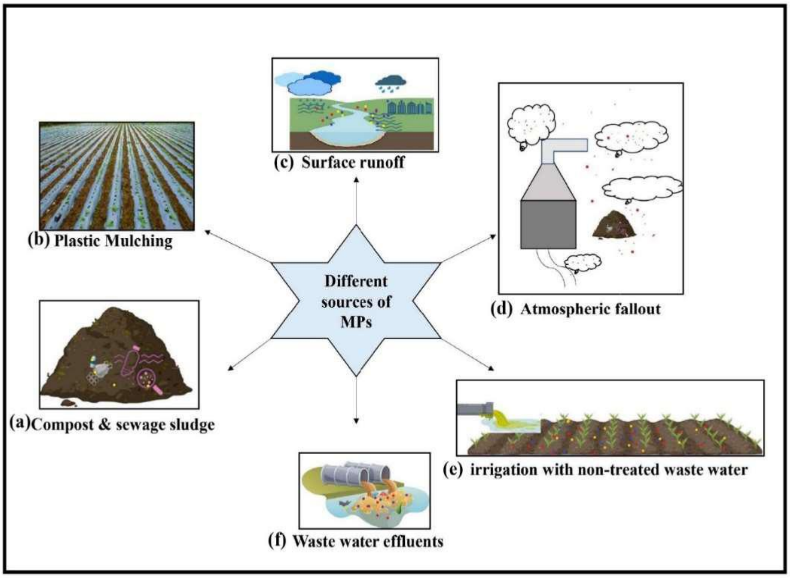

Figure 1: Different sources of MPs (a) Compost and sewage sludge (b) Plastic mulches (c) Surface runoff (e) House hold (e) Irrigation with Non-treated waste water (i) Atmospheric fallout.

The MP contaminants originate from various sources (Table 1), are transported by air and surface water due to their low density, and subsequently deposit into the aquatic environment. Through infiltration, some travel to the subsoil and eventually contaminate the groundwater [9]. According to *cai et al., (2023)* fertilized and mulched farmland exhibits nearly three times greater MPs abundance than non-fertilized farmland [10].

Table 1: Types and Sources of Plastics

S.No	Plastic types	Sources
1	Polyethylene terephthalate (PET)	Drinks and beer bottles, Mineral water, soft drink, food bag pouches, pre-prepared food trays, some shampoo and mouthwash bottles, fiber for clothing and carpets.
2	Polyvinyl chloride (PVC)	Carpet backing, Credit cards other floor covering, door frames, guttering, pipe fittings.
3	High-density polyethylene (HDPE)	Food boxes, Detergents, non-carbonated drink bottles, bleach, fabric conditioner bottles, cereal box liners, toys.
4	Polypropylene (PP)	Ketchup, syrup bottles, most bottle tops, yoghurt containers, biscuit wrappers, drinking straws and plant pots. potato crisp bags, crates.
5	Polystyrene (PS)	Seed trays, Yoghurt containers, food trays, egg boxes, video cases, vending cups, disposable cutlery, and low-cost brittle toys, coat hangers.
6	Low-density polyethylene (LDPE)	Wires and cable applications, Films, refuse sacks, fertilizer bags, packaging films, and some bottle tops, thick shopping bags (clothes and produce).

MPs can enter into the soil and aquatic environment through bioturbation, sewage irrigation, landfills, agricultural mulching films, and flooding [5]. The marine environment accumulates only 20% of total MP debris, whereas the terrestrial and freshwater environments accumulate approximately 80% of it [2]. MPs direct consumption by aquatic organisms, including zooplankton, crustaceans, bivalves, fishes etc., shows unrealized risks such as energy allocation, internal tissue damage, and reproductive abnormalities [3]. MPs can infected the human body through the contaminated drinking water and food chain [3],[11]. Human body affected by MPs (50 nm) entered through food chain from plant tissues [12]. Compared to other water resources, there are very deficient studies on the contamination of microplastics in groundwater and soil bodies [5].

The present review article emphasizes the origin of soil microplastics and their transportation under biotic and abiotic conditions, along with the influence of MPs on soil and groundwater and their ultimate human health consequence.

2. Origin of microplastics in Soil environment:

Soils are the main reservoirs for MPs, and very few studies have been done on the contamination and effect on soil [13]. Some MPs in soil discharge through anthropological activities, while others interact directly with soil, such that some are continuously enriched in the food chain [14]. PP, PE polymers make up the majority of MPs, and most soil MPs are less than 1 mm in size [8], [13].

Agricultural activities with non-treated wastewater are the main source of soil MP pollution [8]. Municipal solid waste landfills are one of the foremost sources of MP pollution, which affects the terrestrial soil and groundwater [15]. Anthropogenic activities such as soil amendments, irrigation, atmospheric deposition, and urbanization generate the various sources of MPs in terrestrial soil, including urban and agricultural soils [16]. Soil contamination due to MPs causes a threat to the soil biota [17]. MPs are introduced into the earth subsurface through various processes as described in the fig. 1 [18], [15].

2.1 Compost

Agricultural activities commonly use compost as fertilizer, and bio-waste compost frequently contains plastics due to improper solid waste disposal. several research studies have shown that accumulation of MPs in compost due to illegal disposal of solid and liquid waste, lack of waste separation, and the use of conventional plastic bags for collecting organic waste [19], [20].

2.2 Sewage sludge

The application of sewage sludge as a fertilizer is a widely accepted practice in agriculture. Since the 1990s, several studies reported the existence of synthetic fibers in sewage sludge, which has become prevalent. Wastewater plants produce sewage sludge that holds more than 90% of MPs. Wastewater treatment (WWT) segregates MPs, which then settle in sewage sludge [21]. The MPs were incorporated in sewage sludge, extensively used in agriculture, affecting agricultural soil and its properties. According to a study *Mahon et al., (2016) and Corradini et al., (2019)*, the soil receives approximately 23 tons of sludge per year, and of this, 7–43 picograms of MPs settle at 0 to 10 cm depth, which is 101 times more than plastic mulching in a year [22], [23].

2.3 Plastic mulching and packing

According to *Y. Huang et al. (2020),* In the soil environment, plastic mulching is a major source of MPs. Plastic mulching is a well-known method to increase the temperature of the soil and reduce water escaping, which increases crop productivity [24]. The most commonly used polymers in plastic mulching are HDPE and LDPE. China, Japan, and South Korea employ nearly 80% of plastic mulching techniques when compared to other countries. Up until 2019, the annual increase in the covered surface with plastic mulching was 5.7%. PVC-containing plastic mulches made up of 50 to 120 mg of phthalates per kg are banned because they are harmful pollution to the soil environment [25].

2.4 Irrigation with non-treated waste and surface water

Wastewater is a primary source of soil contamination with MPs due to its ability to easily transport MPs from various sources [23]. The majority of wastewater contains MP fibers; raw wastewater nearly holds 74% of total MP fibers, and approximately 91% of MP fibers remain in wastewater after treatment. Street runoff water and flood water pass through dump sites, and tire abrasion carries MPs and deposits them in the soil environment [26].

2.5. Atmospheric fallout

Poorly managed landfills, streets, and transportation easily release MPs into the wind, which eventually deposits them in soil [21]. Wind speed and wind directions are important factors in the atmospheric fallout of MPs. As per *G. Chen et al. (2020),* urban areas are more susceptible to MP pollution compared to rural areas. The MPs also contaminate the air along with soil and water. Synthetic materials from textile industries are the main source of MPs in the atmosphere. Small size fibers can be easily separated from clothes and other products and contaminate the air. Degradation of large-size plastics, industrial emissions, traffic emissions, and resuspension of dust particles are also sources of MPs in the air [27].

3. Transportation of Microplastics by soil [Under abiotic and biotic condition]

Soil is the chief sink of MPs, also acts as effective transporter to groundwater. Agricultural and bioturbation activities have the ability to transport MPs over short distances. However, the ingestion of MPs by the soil biota (earthworms etc.,) can have a significant negative impact, leading to a gradual decrease in soil health. Plant roots and soil fauna, such as earthworms and microarthropods, facilitate the vertical migration of soil through plowing, harvesting, and bioturbation methods. Some studies have shown that the vertical transport of MPs can also occur in partially saturated natural soils at a depth of 10 cm, even in the absence of earthworms and microarthropods. Agricultural activities form soil micropores and fractures, which facilitate the vertical transport of microplastics [15]. However, shallow soils contain a greater abundance of MPs than deeper soils [28]. Living organisms in soil, such as plants (particularly their roots), microbial communities, earthworms, and larvae of invertebrates and other vertebrates, influence the substratum, known as bioturbation. Digging mammals, collembolans, and mites etc., transport the MPs into the downward layers of soil. The process of plant root growth and the loosening of soil by earthworms create a large number of pores in the soil that allow MPs to enter. Larger fauna have a higher capability to transport MPs than smaller fauna [5].

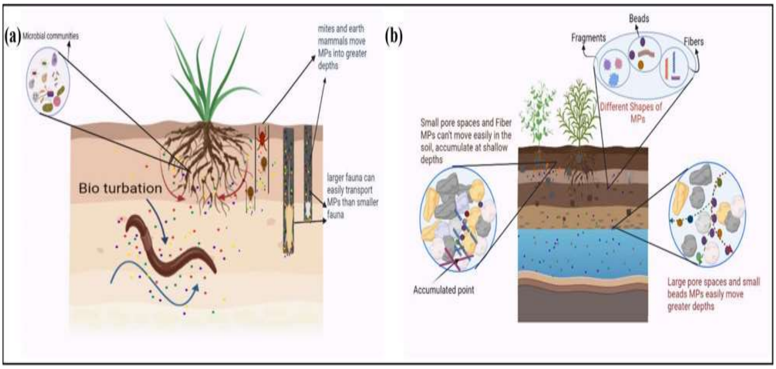

Fig 2: MPs transport (a) Under biotic condition (b) Under abiotic condi tion

Different characteristics, like shape, size, density, surface condition, and charge, greatly influence the transportation and dispersal of MPs under abiotic conditions. The pore size of the soil is directly proportional to the MPs' transportation. Small-sized MPs transport into greater depths than large-sized MPs, and low-density MPs barely move through the soil profile to reach greater depths. Shape heavily influences MP aggregation and blocking effects. Shape greatly influences MP aggregation and blocking effects. Shape plays a crucial role in the transportation of MPs through soil. While microfibers find it difficult to move through deeper layers of soil because they are easily entrapped, MP microspheres easily move through deeper layers of soil. Surface characteristics of MPs, such as hydrophobic and hydrophilic, play a vital role in MPs' migration. Polystyrene particles of hydrophobic character have greater mobility than hydrophilic polystyrenes. The physicochemical properties of soil, like porosity, permeability, ionic property, and organic matter, play a crucial role in MP transportation. Dry climatic conditions form soil cracks. These cracks easily transport MPs to deeper layers [5].

3.1 Effect of Microplastics in soil environment:

Contamination with MPs adversely affects the chemical and physical properties of soil, like porosity, pH, and structures etc., [29], [12]. MPs significantly enhancing chemical properties such as phosphate, organic phosphorus, organic nitrogen, and ammonium nitrogen, which modifies the soil profile and impacts on soil nutrients put greater pressure on plant growth and soil fauna. Some living fauna may eventually die owing to soil MP contamination Microorganism activity is crucial for the decay of soil organic matter and the cycling of vital nutrients that are necessary for root development and plant growth. HDPE pellets experience photo- and thermal-oxidation conditions. Changes in the cation exchange property led to fluctuations in the soil pH value, which eventually affect the soil biota. MPs carry pollutants such as organic impurities, heavy metals, and engineered nanomaterials that deposit and contaminate the soil [5].

Contamination of soil with MP pollution causes severe damage to plant growth. The addition of MPs to the soil environment adversely affects the growth of plants. The addition of HDPE, polylactic acid or polylactide, PE and fiber MPs severely damages soil porosity by reducing the infiltration of irrigation water and rainwater. This, in turn, significantly reduces the soil's water-holding capacity, leading to anoxia. Plastic mulch film greatly disturbs soil porosity and reduces soil permeability and plant root growth[30][31]. Mesofauna, such as mites, collembolans, and earthworms, play a crucial role in maintaining soil quality and health. When mesofauna ingest these MPs, they segregate in the gut and stomach, which ultimately leads to the loss of these organisms [30]. Biophysical properties of the soil (soil structure, pH, soil fertility, soil microbes, nutrition and water stability, etc.,) can affect greatly by the MPs in soil [32]. MP contamination decreases the soil respiration properties [33]. Solar UV radiation disintegrates MPs deposited on topsoil, causing them to migrate vertically and horizontally throughout the soil, thereby influencing its biological diversity [34]. Soil and groundwater interaction is an intricate process; it involves chemical, physical, and biological mechanisms that can impact the MPs transport [35].

4. Origin of Microplastics in Groundwater

Approximately 97% of Earth's fresh water is found in groundwater, making it the world's greatest freshwater reserve [35]. The vertical transportation of MPs can also penetrate deeper layers of soil and contaminate the groundwater system. Recent studies have demonstrated that MPs' agricultural activities, wastewater treatment plants (WWTPs), and anthropological activities also pollute groundwater [9].

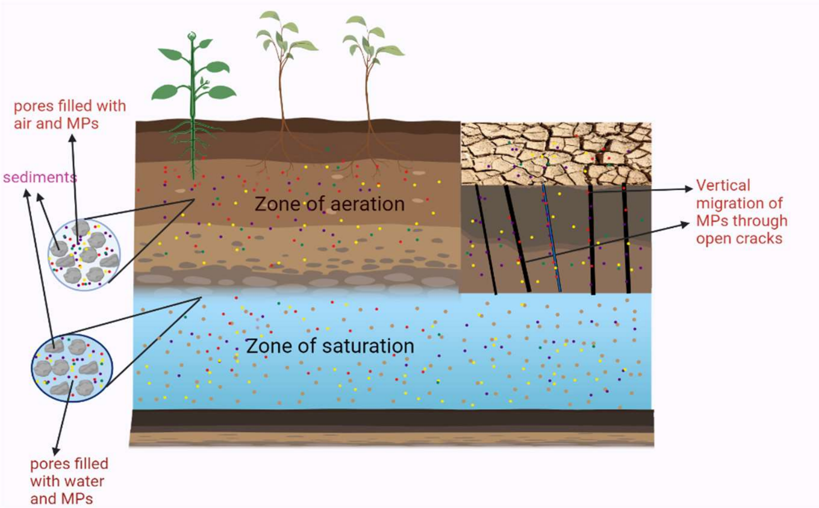

Fig. 3. MPs in Groundwater environment

Panno et al. (2019) explained the deposition of MPs in rainy and arid environments and explained the infiltration of MPs into the groundwater [36]. A few studies reported MP contamination in groundwater. Surface runoffs, wastewater effluents, soil migration, landfill leachates, and human activities are the main sources of groundwater MP pollution. Among the above sources, wastewater effluent and soil migration are the main passageways of MPs to groundwater [8].

4.1 Surface runoff

MPs by Surface runoff water is recognized as the leading cause of the diminution in the quality of groundwater. Storm runoff from urban areas carries so many pollutants that it greatly influences the groundwater system. The first flush of the runoff water carries the greater volume of plastics, along with other pollutants finally deposed in soil after that infiltration causes MPs to go down to groundwater [37].

4.2 Waste water effluents

Wastewater effluents are potential source for groundwater MPs. Sewage pipeline leakage from WWT plants contributes to MP contamination in groundwater. Region where surface and groundwater mixed is named hyporheic zone (HZ). MPs enter through this zone and contaminate the ground water. Sewage effluents contain a substantial number of microfibers. These fibers adversely influence groundwater. MP-contaminated water passes through sinkholes and rock fractures and finally reaches groundwater [37].

4.3 landfill leachates

Large amounts of plastic bury landfills. The pH of leachates varies from 4.5 to 9. Temperature fluctuations, salinity changes, gas generation, and microbial degradation all contribute to the fragmentation of macroplastics into microplastics. This landfill leachate transports MPs into groundwater [38].

4.4 Impacts of groundwater microplastic contamination

Many previous studies revealed the severe impact of MPs on groundwater [15]. Average concentration of pieces in groundwater is about 16 pieces/liter; contamination of groundwater has a very serious impact on human health and environments[9]. *Panno et al., (2019)* studies explain MPs, which come from surface runoff or septic effluent, are found in groundwater aquifers [8]. MPs in soil decrease the retention capacity of Cd and increase its mobility, triggering the possibility that harmful metals like Cd would accumulate in crops and seep into groundwater, posing further hazards to environment and human health [39]. There are many kinds of MPs in the groundwater that come from different places. Polypropylene was better at absorbing Cd, As, Cr, Mn, Cu, Pb, and Zn, while polyamide is better at absorbing Mn. Even at lower As, Cd, and Zn concentrations, polyethylene and polypropylene can absorb metals from the water. MPs could be key for the movement of toxic metals in surface and groundwater systems [40].

5. Microplastics in Environment and Effect on human health

The primary MPs, with a size of <5 mm, released by industrial and domestic products, such as cosmetics, clothes, health products, food containers, and households, contaminate the food and water, which has potential implications for human health [41]. Researchers have conducted a few studies on the impact of MPs on human health and the associated risks. However, many studies focused on the indirect effects of MPs on human health by using mathematical modeling, ecological effects, effects on marine species, and *in vitro* cell culture techniques [42]. Some studies have supported the possibility of MPs ingestion or bioaccumulation by aquatic species at lower trophic levels, which could potentially lead to biomagnification in humans at higher trophic levels [43]. Research has demonstrated that humans come into contact with MPs through various means such as ingestion, inhalation, and dermal contact [41]. Humans are primarily exposed to MPs through the ingestion of MP-contaminated food and water. The estimated consumption of MPs ranges from 74,000 to 121,000 particles per year and per person [44]. MPs typically contaminate the water from various sources, and they primarily contaminate food sources through commercial fish, bivalves, salt, sugar, and crustaceans [45].

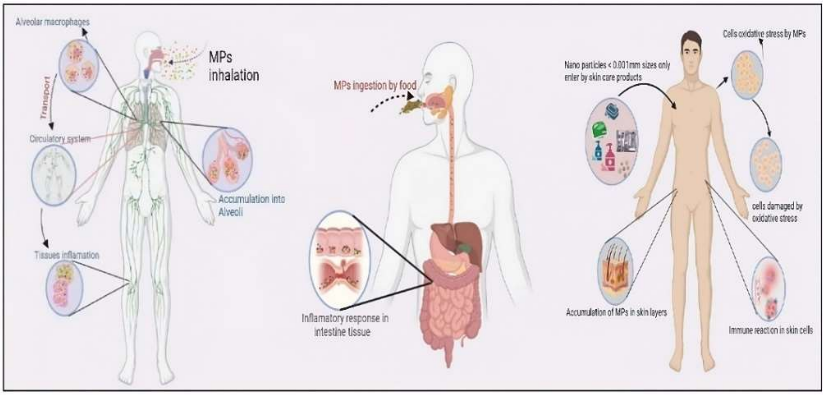

Fig. 4. Microplastic's invasion into the human body

Common microplastic particles found in food products and the environment are polypropylene, polyurethane, polyvinyl chloride, polyethylene-terephthalate, styrene acrylate, polyester, polystyrene, polymethyl-methacrylate, polyethylene, and polyamide [46], [47]. Research indicates that either the internal mucosa directly absorbs MPs, or the intestinal M cells of Peyer's patches engulf them [48]. Ingestion of MPs by humans might lead to damage to the intestinal barrier, cause an inflammatory response, and reduce mucosal secretion in the intestine. It also alters the metabolism of triglyceride synthesis and lipogenesis [49]. The sources of indoor and outdoor microplastics are plastic product abrasions, synthetic textiles, landfilling, and waste incineration [50]. On average, a person can inhale MPs ranging from 26 to 130 MPs, and the respiratory system absorbs and deposits MPs based on particle characteristics such as size, hydrophobicity, surface charge, and density [51]. After inhalation by the respiratory tract, MPs induce the inflammatory response, and lung macrophages engulf the microplastics, which translocates them to the lymphatic and circulatory systems [52].

Synthetic textile industry workers are more prone to the development of interstitial lung diseases such as chronic pneumonia, allergic alveolitis, and asthma-like bronchial reactions [53]. Microplastics larger than 100 nm are unable to be absorbed by the skin, but nano plastics with less than 100 nm can cross the skin barrier and enter into the internal circulation and tissues [54]. According to the Federal Institute for Risk Assessment of Germany, personal care products absorb MPs and microbeads into the skin, leading to skin inflammation and local cell cytotoxicity [55]. Dermal exposure to MPs and nanoplastics causes oxidative stress in human epithelial cells and also induces immune reactions [56]. Humans have observed that MPs cause oxidative stress, inflammation, chronic irritation, and necrosis, accumulate in the tissues, and induce cytotoxicity. These MPs interact with immune cells, leading to a compromised immune system [57], [58]. MPs generate free radicals in the form of reactive oxygen species (ROS), which exist within microplastics during polymerization and processing of plastic products [59]. MPs generate oxidative stress, which denaturates proteins and ribosomes, causing damage to DNA and other intracellular organelles [60].

MPs induce local or systematic immune responses depending upon their distribution and the host immune response [61]. MPs generate oxidative stress, which triggers autoimmune disorders and antibodies against self-antigens [62]. The entry of MPs into the human body occurs through ingestion, inhalation, and dermal contact. These ingested MPs accumulate in the tissues, leading to a systemic inflammatory response and pulmonary hypertension in the circulatory system. This, in turn, enables these MPs to translocate into internal organs like the spleen and liver, resulting in malfunction, chronic inflammation, and an increased risk of neoplasm [63], [64]. An ex vivo study confirmed the presence of polystyrene particles in the placenta, which could diffuse from the mother's blood circulation to the placental membrane [65], [66]. MPs also accumulate in the brain tissues and can cause permanent damage to the neurons. In a study conducted on European seabass (Dicentrarchus labrax) exposed to MPs accumulated into brain tissues, researchers found increased lipid peroxidation, oxidative stress, decreased acetylcholinesterase (AChE) enzyme, and abnormal swimming behavior [67][68]. MPs significantly reduced reproductive success in animals such as hydra, *Daphnia magna*, and others. A study found that Caenorhabditis elegans exposed to nanoplastics accumulated into their gonads, leading to infertility [69], [70].

Although MPs cause chronic inflammation and DNA damage and compromise the immune response, they do not directly cause carcinogenicity [71]. According to a study, the presence of MPs and nanoplastics activates pro-inflammatory cytokines, triggers angiogenesis, and ultimately leads to the development of malignancies [72]. MPs are vectors for persistent organic pollutants (POPs) and microorganisms. POPs, which include bisphenol A (BPA), triclosan, bisphenone, and organotin, are additives added during the manufacturing of plastic products. These POPs do not form any chemical bond with the matrix present on their surface. When MPs contact body surfaces, they easily diffuse through animal tissues [63], [73]. Most microorganisms adsorb on MPs' surfaces, which causes pro-inflammatory responses and carries them to the target sites, leading to tissue infection and damage. These microorganisms can also become opportunistic pathogens when accumulated into tissues [74]. Bisphenol A Commonly found in infant feeding polycarbonate bottles, exposure to BPA at early stages of life enhances the cancer risk in later life. BPA is involved in liver function alteration, decreased brain function, defects in reproductive function, fetal anomalies, and insulin resistance [75]. Phthalate esters might cause abnormal sexual development and birth defects [76].

6. Mitigation strategies:

To predict the impact of groundwater and soil interaction on the source-to-sink process of MPs, a particle migration model is required [35]. Research on MPs in groundwater is still in its early stages, but we must develop different methods to reduce and purify MPs in this environment. Blocking MPs' entry points is necessary to reduce their concentration in groundwater, emphasizing the significance of disposing of plastics properly in soil and agriculture areas. Further research is required to identify methods and technologies for removing and cleaning up MPs that have already contaminated groundwater agricultural. To identify and control the MP contaminants, we must reinforce legislation and regulations. To effectively remove MPs, wastewater treatment systems must be upgraded. To stop additional contamination, MPs should not be added to consumer goods. Instead, biodegradable alternatives should be promoted. In order to decrease the demand for plastic and encourage recycling, public awareness campaigns and responsible consumption programs are crucial. The government can encourage responsible plastic use by implementing environmental taxes and organizing awareness programs [77]. Certain species, such as bacteria, fungi, and mealworms, can biodegrade plastic polymers, reducing plastic pollution without harming the environment. According to *Bombelli et al. (2017),* larvae of the wax moth Galleria mellonella quickly biodegrade PE and producing Ethylene glycol. Similarly, isolated bacteria from the earthworm's (Lumbricus errestris) intestines broke down (LDPE) MPs [78]. Consequently, these organisms have instilled a great deal of hope for the potential application of creatures that consume plastic in waste management. Most importantly, governments must provide funding for more studies and inventions to identify creatures that can decompose plastic more effectively. All of these tactics work together to lessen the. all of these strategies contribute in minimizing the number of MPs in both terrestrial and aquatic habitats [46].

7. Conclusion: `

Microplastics have emerged as a widespread and persistent environmental pollutant, affecting soil, groundwater, and human health. Their presence in soil disrupts vital ecological processes, undermining soil health, agricultural productivity, and biodiversity. Similarly, the contamination of groundwater with microplastics raises serious concerns about the safety of drinking water and the potential risks to human health. While research is still ongoing, early findings suggest that microplastics can have harmful effects on human health, including inflammation, toxicity, and the transfer of hazardous chemicals. Given their persistence and ability to accumulate in food chains, addressing microplastic pollution requires a multifaceted approach, including stricter regulations on plastic production and waste management, increased research on their environmental impact, and public awareness campaigns. A coordinated global effort is essential to mitigate the spread of microplastics, reduce human exposure, and protect both ecological systems and public health for future generations.

Acknowledgments. Not applicable.

Disclosure of Interests. The authors declare no competing interest.

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