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REVIEW ARTICLE

Impact of Microplastics on Soil Environment: A Comprehensive Review

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ABSTRACT
Soils have become an important sink for microplastics due to their increasing presence as global contaminants. Contaminants smaller than 5 mm are microplastics, and the current body of evidence suggests that, unlike polycyclic aromatic hydrocarbons and heavy metals that are temporarily sequestered, microplastics are not biodegraded, and thus, there is an increasing soil microplastic contaminant load for the foreseeable future. Though early research concentrated on microplastics in the ocean, many current studies have shown microplastic contamination of soil due to plastic mulch, sewage sludge and compost, atmospheric deposition, irrigation, tyre wear particles, and improper waste disposal. The purpose of this study is to critically examine and synthesise the research literature on the sources, distribution, fate, and effects of microplastics as soil contaminants, particularly concerning the effects on soil physical properties, chemical contaminants, effects on microbes, soil organisms, and the effects on the sprouting and growing of plants. Increasing microplastic contamination of the soil provides a medium to introduce and demonstrate soil, plant, and human food chain contamination. Moreover, the technical difficulties associated with identifying and quantifying microplastics within soil are discussed. Microplastics soil studies have little research with many areas unresearched, especially concerning field studies, understanding of the contamination of nanoplastics in the soil, and the development of research methods that are consistent. It is important to create effective mitigation strategies for long-term sustainability and soil health to address challenges.
KEYWORDS: *Microplastics, soil pollution, agricultural soils, soil health, terrestrial ecosystems, environmental risk*

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INTRODUCTION

With hazardous materials like asbestos, microplastics are identified as plastics that are smaller than 5 mm. Microplastics are tiny fragments of plastic (less than 5 mm) [1]. Microplastics can be classified as primary or secondary, with secondary microplastics being microplastics from previously larger plastic items. Primary microplastics are still in their original form and can be small plastics made for abrasives or small plastics made for microbead cosmetics [2,3]. These primary microplastics can be small plastic beads that are made for cosmetics or other purposes. While plastic was kept in rigid formats, our understanding of microplastics was aberrated and limited. However, microplastics being integrated into the soil ecosystems call for an understanding of the plastic problem based on soil to water continuums and the laterally connected soil-water management systems [4,5]. This understanding of plastic based problem in soil ecosystems goes beyond basic fugitive plastic theory of our understanding of the problem connected to the soil-water systems that are laterally integrated to the systems and plastic management. Plastics are usually tracked, and their integration into soil systems; however, plastics scattered in the soil ecosystems are often disregarded for their interconnectivity to soil ecosystems. Activities like plastic remediation, urban activities, and the deposition of microplastics from the atmosphere can create a network connected to soil ecosystems and plastics scattered in the ecosystems that would be integrated into the soil ecosystems. For interactive soil ecosystems that support living organisms, microplastics are not sequestered or stripped as available nutrients or plastic particles, but interconnectivity, weak soil continuity, ruins, further scatter and are integrated into soil ecosystems [6]. This interconnectivity can be further killed for the living organisms in soil ecosystems and their humans relying on soil ecosystems, which will, in turn, be microplastics integrated into soil systems for humans relying on soil plastics and microbeads. Why do approximately half of the world's microplastic supply produced rely on the soil ecosystems to manage their harmful scattered systems based on their plastic problem? Soil ecosystems integrated with the microplastic problem? This basic proof. Primary microplastics from urban activities and be produced from the aesthetic plastic-alternatives, scattered plastic beads, and soil aesthetics associated with microplastic integrated soil and microbeads easily manage the microplastic problem [7,8].

Recognition of soil as a sink for microplastics is increasing owing to its ability to gather microplastics from various input pathways, including sewage sludge and compost application, plastic mulching films, irrigation with plastic-contaminated water, and fallout from the atmosphere. Microplastics incorporated in soil will persist for extended periods owing to their resistance to biodegradation and will eventually break down into smaller microplastics [9]. Accumulation of microplastics in soil is a major concern as it will affect the physical structure of soil, harm or alter microbial communities, interact with soil contaminants, and affect how microplastics may move through the soil-plant-food systems. Considering the vital function of soil in ecosystems as well as its role in sustaining agricultural productivity and food security, studying microplastics in soil systems has to be prioritised [10].

SOURCES OF MICROPLASTICS IN SOIL

Microplastic contamination of soil is primarily due to agricultural practices. The use of plastic mulch and greenhouse covering materials has boosted agricultural output significantly, but microplastics are generated in soils from these materials due to ultraviolet light, mechanical breakdown, and repeated soil tilling, which causes the plastic to break down and microplastics to remain soil-bound [11]. Certain plastics, such as low and high-density polyethene and polypropylene, from agricultural activities, are constantly and increasingly being incorporated into agricultural soils, thus inducing the gradual and continuous accumulation of these polymer constituents in agricultural soils [12].

Another significant pathway of microplastics contaminating the soil ecosystem is the land application of sewage sludge, biosolids, and compost. Microplastics are trapped in wastewater treatment plant effluents, get concentrated in the sewage sludge, and, when the biosolids are used as organic fertilisers, microplastics are added to agricultural soils [13,14]. Microplastics are also present in compost derived from municipal solid waste due to poor waste separation, which contributes to soil pollution. Recent studies indicate that atmospheric deposition is becoming a vital source of microplastics in terrestrial ecosystems. Microplastics can originate from synthetic textiles, industrial, and urban emissions. Microplastic deposition can occur through dry and wet deposition, and can occur over long distances. This leads to microplastics being trapped in soil. Also, irrigation with treated wastewater, or contaminated surface water, introduces microplastics directly into the soil of the water-scarce area, where the wastewater is used repeatedly. [15,16]

Urbanisation is an important contributor to microplastic pollution in soil. Vehicle tyres create microplastics and become a major contributor to microplastics found in roadside soil. These particles are also transported via stormwater runoff into nearby land areas [17]. Leachate from landfills, littering, and inadequate management of plastic disposal create a localised microplastic contamination because large plastic debris is weathered and fragmented in the soil and landfill [18].

DISTRIBUTION AND ABUNDANCE OF MICROPLASTICS IN SOIL

Microplastics have been found in all regions of the terrestrial environment, including agricultural fields, urban soils, industrial regions, and even soils from remote and natural ecosystems [19] (Table 1). Due to differences in land use, sampling depth, and local sources, the abundance of microplastics can vary by several orders of magnitude (ranging from a few hundred to multiple millions of microplastic particles recorded per kilogram of dry soil), and depending on the analytical method used, there is a recorded range from a few hundred to several million particles per kilogram of dry soil [20]. Agricultural soils have been shown to have larger amounts of microplastics compared to natural soils; this is due to the ongoing and continuous addition of microplastics in biosolid applications, plastic mulching, and irrigation practices [21].

Microplastic abundance in soils is largely impacted by the way land is used or managed. Drawn from multiple studies, soils from intensely managed agricultural lands and urbanised areas are found to have considerably higher amounts of microplastics in contrast to soils from forest or grassland areas.

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Microplastic particles are found mostly within the upper 20 cm of the soil, largely because it is the top layer where plastic particles are first introduced [22]. Microplastic particles can be found at much deeper soil layers (subsoil) due to certain soil displacement processes, including bioturbation, root growth, tillage, and water percolation. Microplastics that are in the form of particles or fibres in small sizes are more likely or more readily to be transported to the subsoil layers as compared to larger microplastic particles [23].

Microplastics' physical characteristics help us understand their distribution. Fibres are usually the most abundant type of microplastics found in urban and atmospheric deposition regions, while more fragments and films are found in agricultural soils. Also, the type of polymer dictates vertical distribution [24,25]. Flexible low-density polymers like polyethene and polypropylene are located near the upper soil horizons, while higher-density polymers can be found at greater depths due to vertical migration. Distribution and movement of microplastics in soil are show in Figure 1.

Table 1: Distribution of microplastics in different soil environments

Soil type / land use	Dominant microplastic types	Typical abundance (particles kg^{-1})	Major sources
Agricultural soils	Films, fragments, fibers	10^3–10^6	Mulching films, biosolids, irrigation
Urban soils	Fibers, tire wear particles	10^4–10^7	Atmospheric deposition, traffic, runoff
Industrial soils	Fragments, pellets	10^5–10^8	Plastic processing, waste handling
Forest soils	Fibers, fragments	10^2–10^4	Atmospheric deposition
Grassland soils	Fibers	10^2–10^5	Long-range transport, grazing activities

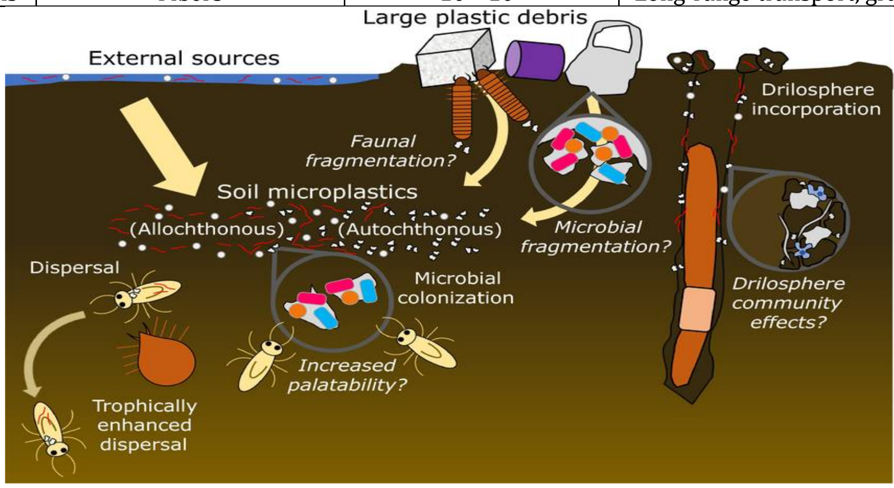

Figure 1: Distribution and movement of microplastics in soil

FATE AND TRANSPORT OF MICROPLASTICS IN SOIL

Once in the soil environment, several physical, chemical and biological mechanisms determine the fate and transport of microplastics. Microplastics are an enduring contaminant, as a result of their persistence and resistance to biodegradation, and can remain within soils for long periods of time [27]. Therefore, microplastics must not be considered as a transient pollutant. Microplastics behaviour within soils is influenced by particle characteristics (e.g. size, shape, density, polymer type, etc.) as well as the characteristics of the soil itself (e.g. texture, organic matter content, moisture, biological activity, etc.).

Fragmentation and Ageing Processes

Soil microplastics are continuously aged and fragmented by ultraviolet radiation, mechanical abrasion, temperature changes, and microbial activity. The processes described result in the oxidation of microplastics and the creation of surface irregularities and increased surface cracks [28,29]. Such changes will also increase the reactivity of microplastics and promote their interaction with soil constituents. As time goes by, larger microplastics are more likely to be fragmented into smaller entities in the soil environment, including nanoplastics, which are proven to be more mobile and bioavailable in soil than larger microplastics [30].

Vertical and Horizontal Transport

Microplastics are first brought to the soil surface, and the majority of research has reported downward movement of microplastics into deeper soil layers. Vertical transport takes place through soil organisms (earthworms), bioturbation, infiltration of percolating water, root growth, and agricultural tillage. Smaller

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microplastic particles and fibres are more susceptible to leaching and can infiltrate subsoil horizons, which poses a risk to the contamination of underlying groundwater systems [31,32].

Surface runoff, soil erosion, flooding, and wind–especially in bare and disturbed soil–promote the horizontal transport of microplastics. Horizontal transport is also aided by agricultural practices (e.g., ploughing and harvesting), which redistribute microplastics laterally within and between fields, and is a primary reason for the distribution of microplastics in the environment [33,34].

Interaction with Soil Components

Microplastics strongly adhere to soil minerals, organic matter, and soil microbial biofilms, leading to influences on particle retention, aggregation, and transport behaviours. Weathered microplastics have greater sorption capacity for organic compounds and heavy metals, which could change the mobility of the microplastics and their associated contaminants. A "plastisphere" (the assemblage of a specific microbial community associated with plastic) can also influence the degradation and transport pathways of microplastics in soils [35-37].

Creation and Transport of Nanoplastics

Microplastics can fragment into smaller pieces known as nanoplastics (<1 μm). Even more concerning, nanoplastics have an increased surface area per volume, and can easily penetrate small pores in soils or root tissues, and can cross biological membranes [38]. However, limitations in analysis have led to gaps in our understanding of nanoplastic transport and fate in soils [39].

Microplastic transport and fate in soils is an outcome of a multitude of interrelated environmental processes, leading to complex and highly variable processes that, depending on the context, could lead to microplastics becoming concentrated, re-distributed, or altered in transformation within terrestrial ecosystems. The more we understand these processes, the easier it will be to predict their environmental consequences and the more effective our containment strategies will be. Conceptual diagram illustrating the fate and transport of microplastics in soil are shown in Figure 2.

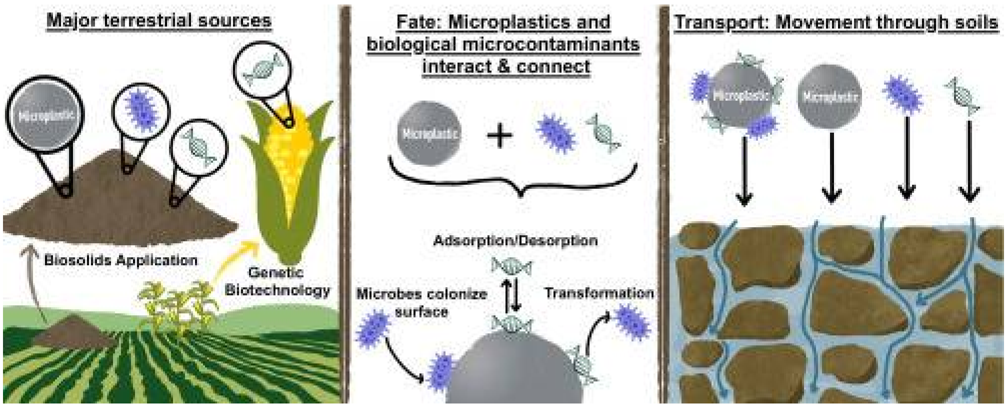

Figure 2: Conceptual diagram illustrating the fate and transport of microplastics in soil.

EFFECTS OF MICROPLASTICS ON SOIL PHYSICAL CHARACTERISTICS

Microplastics in soil have been demonstrated to alter soil physical properties that are vital for soil functioning and for the growth of plants. Microplastics affect soil structure by altering soil aggregation, bulk density, porosity, and the soil's water-holding capacity. These soil microplastic effects are especially influenced by the size, shape, concentration, and specific polymer type of the microplastics, as well as the soil texture and the quantity of organic matter in the soil [40,41].

Studies have documented that fibrous and film-like microplastics can reduce soil bulk density as well as increase macroporosity, and while soil aeration is improved, soil water retention is compromised [42]. In the other extreme, microplastic fragments can disrupt soil aggregates by breaking the bonding forces of particles, thus reducing aggregate stability and making soil more susceptible to erosion [43]. Soil pore structure changes can alter hydraulic conductivity, decrease the rate of flow in soil, and make changes to the soil moisture structure and the transport of nutrients.

In this regard, the long-term build-up of microplastics in soils that are repeatedly cultivated may erode the structural stability and resilience of soil, and this can have negative consequences for agricultural productivity and the services that are provided by the ecosystem [44]

Chemical Interactions and Contaminant Transport

Microplastics contain active chemical agents in soil systems. Their large surface area and hydrophobic characteristics allow them to attract many types of organic pollutants and even heavy metals, such as cadmium, lead, and mercury [45]. These include pesticides and antibiotics, as well as polycyclic aromatic hydrocarbons. Sorption capacity is further enhanced through the ageing and weathering process that creates surface roughness and introduces new oxygen-containing functional groups to the surface of microplastics [46].

Microplastics, in addition to being a vector for other contaminants, can leach into the soil environment deleterious plastic additives, such as phthalates, bisphenols and flame retardants. These plastic additives can contribute to soil ecosystem problems and may even pose a risk to the soil environment. Soil microfauna and plants can be affected through changes in the bioavailability, mobility, and persistence of microplastics and contaminants, and pose a risk to their natural environment [47,48]. Microplastics and chemical contaminants in the soil signal their ability to modify the fate and transport in soil [49].

Impact of Microplastics on Soil Microbial Communities

Microorganisms in the soil are vital for the cycling of nutrients, decomposition of organic matter, and overall health of the soil. It has also been proven that soil microplastic contamination alters the composition, diversity, and activity of soil microbial communities. Microplastic particles act as a substrate for the colonisation of microorganisms, causing the development of a new type of biofilm, the "plastisphere"[50] Microplastics have also been shown in experimental studies to inhibit soil enzyme activity (dehydrogenase, urease, and phosphatase) that affects the cycling of carbon, nitrogen, and phosphorus. Changes to microbial respiration and biomass have been observed and are dependent on the type of microplastic, the concentration, and the time of exposure. Microplastics may inhibit the activity of a microbial taxa while perhaps even stimulating the activity of others [51,52]. This situation may also cause a shift in the overall functional capabilities of the soil ecosystem. It is vital to understand that alterations to the microbial community due to microplastics are a serious concern because the microorganisms are responsible for soil fertility and the overall stability of the ecosystem [53,54].

Impacts of Microplastics on Soil Fauna

Soil fauna is essential in soil structural preservation, nutrient cycling, and decomposition of organic material. Microplastics are potentially soil-dwelling organisms through ingestion, blocking, and chemical toxicity, and numerous studies have provided evidence to support this claim. In soil, invertebrates such as nematodes and collembola are most exposed and vulnerable to the microplastic contaminants [55]. Earthworms are often the chosen model organisms for studying the environmental effects of microplastics in soil. Microplastic ingestion has been shown to impair the worms' growth, reproduction, and burrowing activity, and this could lead to oxidative stress and damage to the worms' tissues. This means, in the earthworms' burrows, they redistribute microplastics, which helps to give them more potential to be bioc to be bioavailable [56,57]. Microplastics can also increase the soil fauna's exposure to heavy metals and organic pollutants in the soil through contamination, and increase soil contaminants. Microplastics can also increase excessive exposure to chemical pollutants in soil, which can be detrimental to soil fauna. Microplastics have the potential to undermine the vital soil fauna that support the fundamental functions of the ecosystem and the soil [58,59].

Microplastics in Soil and Their Effects on Plant Growth and Productivity

Microplastics do have a direct influence on plant structure and overall productivity, given the presence of microplastics in soil. Studies show that microplastics impede seed germination, the structure of a plant's root system, the plant's ability to absorb nutrients, and how well the plant undergoes the process of photosynthesis. All of these effects are dependent on how concentrated the microplastics are, the type of polymer, the size of the particles, and their moulds [60,61]. Microplastics disrupt the physical structure of soil by affecting its porosity and the ability to retain water. This, in turn, disrupts root system structure and the ability to absorb water in the soil. Additionally, smaller microplastics (nanoplastics) stick to the surface of roots, or are able to move into tissues of the plant (during root system fractures) and branch junctions, and are of great concern as internal accumulation [62].

Some crop species (including wheat, lettuce, and tomato) have significant reductions in biomass and yield, even with microplastics. Other studies show that at low levels, there are actually positive results. All of these studies show there are still a significant number of unexplained interactions that still have more work to be understood [63,64].

RISKS TO HUMAN AND ECOLOGICAL HEALTH

The presence of microplastics in soil poses risks to human and ecological health. Soil acts as a vital interface among environmental compartments and the food web. Through human dietary exposure, microplastics can migrate from soil to plants, soil fauna, and livestock [65].

Aside from their physical presence, microplastics and the chemical additives and absorbed pollutants to which microplastics are coupled are thought to have the potential to produce toxicological impacts [66].

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While there may be no direct evidence of exposure pursuant to a soil-derived pathway, long-term exposure may disrupt endocrine function, cause inflammation, and increase oxidative stress [67].
From an ecological perspective, microplastics in the soil can, in the long run, have detrimental impacts on soil fertility, biodiversity, and the ability of ecosystems to withstand and recover from disturbances. Given the role of soil in food production and environmental sustainability, it is vital to understand and mitigate the microplastic problem to preserve ecosystem services and safeguard public health [68]. Transfer of microplastics through the soil–food–human continuum is shown in Figure 3.

Figure 3: Transfer of microplastics through the soil–food–human continuum

FUTURE PERSPECTIVES

Research into soil microplastics is still developing and leaves much to be desired. For example, research on the detection and quantification of microplastics using environmental standardised methods is virtually non-existent. Additionally, lots of research is done using short-term lab studies, yet there is still the opportunity to do longer studies that utilise real-life field conditions. More research is needed going forward to determine the chronic effects of microplastics, the interactions of microplastics with various soil ecosystem stressors, and the impacts microplastics have on soil ecosystem services. The development of new analytical methods, harmonised soil microplastic research methods, and a combination of soil science, environmental policy, and toxicology will facilitate comprehensive soil microplastic risk assessments.

CONCLUSION

Microplastics are everywhere in the soil and are known and unknown pollutants. Microplastics from agricultural activities, waste management, urban activities, and air deposition are absorbed in the soils. Microplastics are shown to change the physical characteristics of soil, interact with other harmful soil pollutants, alter soil microorganisms, and decrease the activity of soil animals and the health of soil plants. The understanding of the problems that soil microplastics present has advanced, but there are still many unknown problems. These unknown problems will be the focus of future studies and research. Microcontinent pollution in the soil will not be easily resolved, but it must be prioritised. Preserving soil health will be important in the overall health of rural areas and the health of the ecosystem.

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