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THE GROWING PROBLEM OF SOIL POLLUTION WITH MICROPLASTICS: A REVIEW

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Abstract

The growing problem of soil pollution with microplastics represents a serious, ubiquitous global threat with significant implications for human health and ecosystems, and agricultural lands are especially at risk. The accumulation of microplastics, especially those smaller than 5mm in size, disrupts the basic physicochemical properties of soil, including its structure, porosity, and water retention capacity. It also negatively impacts soil microbial communities and their activities, which are crucial for soil fertility. Additionally, it inhibits plant growth, causes oxidative stress and allows the transfer of these particles into plants, posing a direct risk to the food chain and human health. Considering its persistence in the environment and its ability to adsorb and transport toxic chemicals, it's necessary to consider establishing a standardized methodology for research and ecological risk assessment as well as developing effective strategies for reducing microplastic input into soil and remediating highly contaminated areas.

Key words: *Microplastic, pollution, soil, ecosystems, environmental impact*

Introduction

Given that plastic is a more durable and resistant material, it has become the primary choice for packaging of almost all products, as well as for use in the automotive industry, construction, and household appliances. Today, it is impossible to imagine life without plastic, as it is present everywhere around us, and even within us. All ecosystems of planet Earth are contaminated with microplastics. Microplastics pose a particular threat due to the small size of the particles, which accumulate throughout the entire ecosystem in various ways, yet are not subject to natural degradation processes. Smaller particle diameters circulate more rapidly through ecosystems and accumulate in living organisms, soil, air, and water. Microplastic pollution in terrestrial ecosystems has received considerably less attention compared to pollution in aquatic or marine ecosystems [1].

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The negative effects of microplastic contamination are manifested through multiple pathways. They include adverse impacts on soil quality, particularly in terms of porosity, aggregate stability, water balance, gas exchange, and the content of organic and mineral matter. Microplastics also affect plant metabolism by reducing germination capacity, disrupting photosynthesis and root system function, and inducing oxidative stress. Furthermore, they exert stress-related effects on soil fauna, especially by interfering with reproductive cycles. A significant concern is the ability of microplastic particles to adsorb heavy metals and pesticides, which not only deteriorates soil quality but also facilitates the transfer of these toxic substances through the food chain, ultimately posing risks to human health. In addition, the deposition of microplastics in adipose tissue has been shown to negatively influence mammalian hormonal regulation.

The United Nations Environment Program has recognized plastic pollution as the most relevant terrestrial ecosystem pollution [2]. As ubiquitous materials of a modern lifestyle, plastics are used exten-sively worldwide in a variety of contexts. Around 4.9 billion metric tonsare produced yearly, and ≈60% of all plastics are disposed of and are accumulating in landfills and the environment. However, if the managment trends of waste will continue, it is predictable that ≈12 billion ofplastic waste will end up in landfills or the terrestrial system by 2050 [3]. Plastic pollution in agricultural soils has receivedincreasing attention because it is put in direct contact with plasticfrom intentional use (e.g., plastic mulch, plastic greenhouses, plastic-coated products) or from using plastic-contaminated supply of sewagesludge, compost, and irrigation water [4,5].

Literature review

This study employed the method of analysis and synthesis of available scientific and professional literature. The review encompasses the following sources: scientific papers, books, reports from international organizations, and relevant electronic databases.

The primary material used consists of published research in the field of environmental protection, available in databases such as Google Scholar, Research Gate, PubMed, and Scopus.

The methodological framework of the study is based on:

- Comparative analysis of various sources
- Descriptive method (description of relevant theoretical and empirical findings)
- Synthetic method (integration of data from multiple sources into a cohesive whole) Special attention was given to a critical review of the findings and the identification of the main ecological challenges related to the presence of microplastics in soil.

Origin and nature of microplastics in soil and physico-chemical nature of microplastics

The term microplastic refers to microscopic plastic particles, plastic particles that are less than 5 mm in size [6]. There are various types of microplastics that persist in the environment, such as polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), polyamide 6 (PA6), and polyamide 66 (PA66) [7]. These are distributed in the environment in various form and concentrations that are explained below.

Table 1. Different types of microplastics and their densities [8]

Microplastics	Chemical formula	Degree of Crystalinity	Density (g/cm^3)
PE	$(C2H4)n$	Semi-crystalline	0.92-0.97
PP	$(C3H6)n$	Semi-crystalline	0.88-1.23
PVC	$(C2H3Cl)n$	Amorphous	1.15-1.70
PS	$(C8H8)n$	Amorphous	1.04-1.50
PET	$(C10H8O4)n$	Amorphous	1.30-1.50
PA6	$(C6H1NO)n$	Semi-crystalline	1.12-1.14
PA66	$(C12H12N2O2)n$	Semi-crystalline	1.13-1.38

Established agricultural practices are the dominant source of microplastics in soil. However, all anthropogenic activities, particularly inadequate disposal and treatment of plastic waste, have a significant impact. Partially degraded plastic waste exposed to sunlight and oxygen further breaks down, and microplastic particles penetrate deeper soil layers. Through the activity of soil fauna, these particles are distributed both horizontally and vertically in the soil. In addition to persisting in the soil and causing numerous negative effects on soil quality and living organisms, microplastic particles can be transported by water, contaminating watercourses and spreading to distant locations from the point of contamination.

The problem is highly concerning because it takes approximately 20–500 years for microplastic substances and structures to degrade [9].

Dynamic sources of microplastics include urban dust, tires, synthetic textiles, road markings, marine surface coatings, personal care products, and plastic pellets [10].

The main sources of microplastics and nanoplastics include wastewater treatment processes, microbeads, clothing fibers, plastic debris, and cleaning and care products [11]. It has been observed that biosolids significantly contribute to microplastic pollution in agroecosystems, with approximately 430,000 tons in Europe and 300,000 tons in North America [6]. Further transport of microplastic particles into deeper soil layers is driven by leaching, bioturbation, or anthropogenic activities such as mechanical plowing.

Microplastic will be trapped in the soil unless its size is smaller than the pore diameter of the soil. However, the movement of microplastic in both vertical and horizontal directions is determined by various factors. Soil properties, including texture and organic matter content, significantly influence the retention and migration of microplastic. Due to its lower cohesion, sandy soils tend to allow greater movement of microplastic compared to clay-rich soils. The retention of microplastic in soils dominated by quartz sand can be enhanced by increasing the ionic strength. Under the same conditions, and considering that soil is a complex and heterogeneous medium compared to homogeneous quartz sand, the transport of microplastic is affected by the surface roughness of the medium, biofilm formation, organic matter, saturation, and hydrodynamic conditions [12].

Impact of microplastic on soil quality and its components

Impact of microplastic on soil quality

The presence of microplastic alters soil structure by directly affecting soil density, chemical–organic composition, and the distribution and size of soil pores. It has been shown that there is a correlation between the presence of polyester microfibers (microplastic) and soil density. As the density of these fibers increases, the soil becomes more porous [13]. The presence of microplastic also weakens the physical forces that bind soil aggregates, directly affecting soil stability—specifically, the soil becomes less resistant to erosion. Additionally, the instability of soil aggregates disrupts the balance of water, air, and nutrients.

A very important factor that dictates water drainage dynamics and availability to the plant root system is the size and arrangement of soil pores. Soil becomes saturated with water when pores are smaller. In such cases, water is physically present but unavailable to plants, and the soil loses its capacity for proper drainage.

In the scientific paper Impacts of Microplastics on the Soil Biophysical Environment, published in the journal Environmental Science & Technology (Vol. 52, Issue 17), Anderson Abel de Souza Machado; Chung Wai Lau; Jennifer Till; Werner Kloas; Anika Lehmann; Roland Becker; and Matthias C. Rillig investigated the diversity of microplastic particle models to increase the validity of claims that microplastic particles affect the considered soil properties.. They found that the tested types of microplastic (polyacrylic, polyester, and polyethylene particles) remained intact five weeks after being introduced into experimental soil. Although they did not undergo degradation during this period, stereomicroscopic observations revealed that they had integrated into the soil matrix. Polyethylene fragments interacted with other soil particles, while the linear shape of polyacrylic and polyester fibers formed a skeleton for larger soil aggregates. The authors hypothesized that such effects of microplastic on soil aggregate formation could influence soil erosion, which could be a subject for further research.

Soil microbiota plays an essential role in the functioning of agricultural ecosystems. It governs nutrient cycling, organic matter decomposition, and soil fertility—all of which are vital for sustainable agriculture. If microplastic disrupts microbial communities, it could lead to poorer soil health and reduced crop yields. Despite the importance of microbiota, the mechanisms by which microplastic affects it are still unknown [14].

Impact of microplastic on plants

Vascular plants serve as microplastic sinks because the plant surface is capable of absorbing MPs [15]. When microplastics enter the soil, they undergo natural processes that change their properties and behavior, and included are microplastic weathering and a loss of physical integrity due to the combined actions of oxidants, UV radiation and mechanical stress [16]. Natural process helps microplastics to decay and this occurs faster in larger plastics that have higher surface-to-volume ratios [17]. Generally, microplastics cannot enter plant bodies directly due to their large size [18]. On the other hand, NPs are capable of entering plant tissues [19]. From rooth NPs can be transferred to stems, leaves, and fruits by water transportation systems [20]. plastic particles accumulate in the flowers, leaves, fruits, and different plant parts, but microplastic uptake, translocation, and accumulation vary from plant to plant [21].
The most significant negative effects of microplastic on plants include potential germination failure in some plants [22, 23, 24], plant damage from cytotoxic elements of microplasti [24], increased and thinned roots [25,26], induction of oxidative damage [24] and deterioration of plant quality [27, 28].

Microplastic stress in plants

MP stress also reduces plant growth and development by altering several key physiological processes including ionic homeostasis, redox regulation, and photosynthesis [29]. Nonetheless, MP-induced negative effects on plant growth and development depend on MP type and dose-dependent effects [30]. In plants, MP stress has a direct interaction with the plant roots because MPs can be adsorbed onto root hairs, thus affecting root growth [22]. Whereas in leaves, MP stress most likely causes oxidative stress, thus reducing leaf growth and photosynthesis [20]. Nonetheless, there is no explicit explanation of how MPs induce toxic effects on plant growth and development [30].

Negative impact of microplastic on soil fauna

Microplastic has harmful effects on soil organisms such as earthworms, nematodes, and mites. Microplastic can bioaccumulate within food chains, which may negatively affect organisms at all trophic levels. Direct biotoxicity to soil microorganisms can result from oxidative stress caused by reactive oxygen species (ROS) and/or the toxic effects of MP additives that have leached into the soil. The presence of microplastic in soil reduces microbial activity and can indirectly affect plant germination by modifying plant nutrition. It has been found that the introduction of low-density polyethylene microplastics into dry soil at concentrations of 0.2 to 1.2% (w/w) is harmful to earthworms, ultimately leading to their death [31].

Methods for soil decontamination from microplastic

The installation of micro-filters in wastewater treatment plants can help reduce contamination by microplastic materials in terrestrial ecosystems, including agroecosystems [30].
Microplastic polymers can undergo hydrolysis due to the presence of microbial strains that produce enzymes and break down chemical structures. Microbial enzymes have catalytic potential due to catalytic sites with amino acids; therefore, different strains of fungi and bacteria can induce biodegradation. For example, Bacillus gottheilii (a Bacillus bacterium) mediated chemical changes and bond cleavage, resulting in a reduction of the bioavailability of PS microplastics [32]. Similarly, the strain Lysinibacillus JJY0216 reduced the weight of PE and PP microplastics by 9% and 4%, respectively, and produced various oxidative products containing CH_2 groups during degradation [33].

Conclusions

So far, numerous studies have been conducted on the occurrence and ecological effects of microplastic in marine and other aquatic ecosystems, but in the case of terrestrial ecosystems, such studies have been limited. Consistent criteria for assessing microplastic contamination are lacking, which has resulted in a lack of comparability of existing research data. Today, stereomicroscopy, Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy are widely used for microplastic detection. Pyrolysis gas chromatography (TED GC-MS), thermogravimetry (TGA), and time-of-flight secondary ion mass spectrometry (TOF-SIMS) have also been employed for detection. However, these detectors are expensive. Therefore, it is necessary to explore other detection tools for future research. In addition, methods of analysis need to be unified and standardized for future studies [1].
Current data are insufficient to analyze the overall status of soil contamination by microplastic at global or regional levels. Clearly, future studies need to consider trophic transfer and transgenerational effects. This should include investigations of natural and urban ecosystems, including plants, and natural microbial communities that respond to microplastic contamination in soil [34].
Key strategies should include reducing the use of plastics in agriculture, improving recycling and waste management systems, and promoting the adoption of biodegradable materials. Strengthening regulations and fostering international cooperation will be crucial in mitigating microplastic pollution at its source. Furthermore, the development of technologies for monitoring, preventing, and removing microplastic from agricultural soils will be vital for protecting both environmental health and agricultural productivity [35].

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