MAS Journal of Applied Sciences
Uygulamalı Bilimler Dergisi
ISSN: 2757-5675
masjaps.com

OPEN ACCESS

DOI: http://dx.doi.org/10.5281/zenodo.13293398

Review Article

The Unseen Threat: The Devastating Impact of Microplastics on Soil Health; A mini Review

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Received: 07.05.2024 **Accepted**: 15.06.2024

Abstract

The presence of microplastics (MPs) in soil has emerged as an urgent environmental issue with the potential to impact soil health and ecosystem functioning. These small plastic particles, usually smaller than 5 mm, enter soil environments through various pathways, including direct deposition from the atmosphere, the application of contaminated organic amendments such as sewage sludge or compost, and runoff from landfills or agricultural activities. Once in the soil, microplastics (MPs) can persist for long periods due to their resilient nature and can enter into complex interactions with soil components. The presence of MPs in soil can alter soil physical, chemical, and biological properties, affecting essential soil functions such as water retention, nutrient cycling, and microbial activity. Furthermore, MPs can interact with soil organisms, disrupting their behavior, reproductive processes, and overall ecosystem dynamics. Additionally, MPs can adsorb and transport harmful chemicals, potentially affecting soil and groundwater quality. Understanding the sources, fate, and effects of MPs in soil is crucial for mitigating their environmental impacts and protecting soil health. Effective strategies to address the problem of MPs in soil include improved waste management practices, regulation of plastic use, the adoption of sustainable agricultural practices, and research into innovative remediation techniques. Addressing the problem of MPs in soil is essential to maintain the integrity and functionality of terrestrial ecosystems.

Keywords: Microplastics, pollution, soil health, microorganisms

1. Introduction

The urgent need to take action against microplastic (MP) pollution in soil is highlighted by recent findings that emphasize protecting soil health and biodiversity. Our fight against MP pollution should involve several strategies: reducing plastic use at the source, improving waste management, and developing new technologies to clean up soil. By addressing these complex challenges, we can work towards restoring and maintaining healthy and resilient soil ecosystems for future generations. Plastics, praised for their versatility and affordability, have become a mainstay in our development (Hale et al., 2020). However, their ever-increasing production (reaching 230 million tonnes by 2009 and projected to hit 1.1 billion tonnes by 2050) has led to a major environmental issue: plastic pollution.

Human activities from shipping to tourism are the main culprits behind plastic entering our oceans (Derraik, 2002; Browne et al., 2010). But the problem goes beyond our seas. Recent research reveals a significant and concerning presence of microplastics (fragments and fibers) in soil (Zhou et al., 2020). Sewage sludge application in agriculture seems to be a major contributor (Van den Berg et al., 2020), with greenhouses showing a rise in microplastics derived from plastic covers. These tiny plastic particles can linger in the soil for extended periods, potentially entering the food chain as they are not readily absorbed by plants (Guo et al., 2020). This contamination is a threat to both urban and agricultural lands.

While the impact on oceans receives more attention, estimates suggest land receives 4-23 times more microplastics (Horton et al., 2017). These plastics can act like a reservoir, potentially leaching into groundwater. Their persistence (lasting centuries) disrupts soil properties, impacting everything from air and water flow to overall soil health (Cole et al., 2011; de Souza Machado et al., 2018; Khatun et al., 2022). Studies even show a negative effect on plant growth, organisms, and root development (de Souza Machado et al., 2019; Pignattelli et al., 2020; Jiang et al., 2017; Wang et al., 2020). Alarmingly, research suggests plants can even absorb these microplastics (Li et al., 2019, 2020a, 2020b).

The impact goes beyond just physical properties. Microplastics can alter soil's chemical makeup, affecting pH, fertility, and microbial activity (de Souza Machado et al., 2019). They integrate into soil aggregates, crucial for structure and organism habitats (Guo et al., 2020; Rillig and Lehmann, 2020). This ultimately reduces soil density, hindering the overall function of the soil system (Yang et al., 2021). There are some potential mitigating factors. The surface layers of soil can degrade some microplastics due to factors like UV radiation and higher temperatures (Chae and An, 2018). Soil microbes and agricultural practices might also play a role in breakdown. However, these processes are incredibly slow, with studies showing minimal weight loss of microplastics even after extended periods.

Microplastic contamination in soil is a growing threat with serious consequences. Further research is crucial to understand the full scope of the problem and develop solutions to protect our vital soil ecosystems.

2. For the determination of microplastics; soil sampling, transport to the laboratory and analysis

Taking soil samples is crucial for studying microplastics (MPs) in agricultural lands. Typically, samples are collected from the top 30 cm, which is the layer affected by plowing (Xu et al., 2019, 2020). Stainless steel shovels are ideal tools for this task (Ding et al., 2020), and a sample size of 20x20 cm is recommended. Researchers also use smaller sampling units (Corradini et al., 2019; Crossman et al., 2020; Du et al., 2020; Feng et al., 2020; Zhang et al., 2020). To preserve the integrity of the samples, it's recommended to sieve them on-site, measure soil pH and color using appropriate tools, and then store them in aluminum bags at 4°C before air-drying. This ensures that moisture content doesn't affect later analysis of microplastic concentration (Yang et al., 2021).

After air-drying, soil samples are usually sieved through a 1-2 mm mesh sieve to isolate microplastics (Wang et al., 2019). Samples with a lot of plant residue might require additional sieving on-site to remove any leftover material (Hidalgo-Ruz et al., 2012). Extracting microplastics from soil rich in organic matter often involves using hydrogen peroxide (H_2O_2), with 30% being the most common concentration used in studies (Hurley et al., 2018). This method is particularly effective for soils with low organic carbon content (Hurley et al., 2018). Another option is the Fenton reagent, which combines hydrogen peroxide and iron (II). This is a preferred method due to its minimal environmental impact (Yang et al., 2021; Zhou et al., 2020).

Density separation is a common technique for microplastic extraction. This involves using solutions like saltwater (NaCl) or other salts. Sodium chloride solution (at 1.0 g/cm^3) is a popular choice because it's readily available, affordable, and safe (Han et al., 2019; Li et al., 2020). After extraction, the dried soil samples are weighed and then treated with a strong salt solution (5 M NaCl). This solution is then centrifuged and filtered multiple times to effectively collect microplastics (Dioses-Salinas et al., 2020).

While microplastics were first discovered in the ocean (2004), research on their presence in soil is a recent development (Rillig, 2012). Surprisingly, studies suggest there may be 4-23 times more microplastics in soil compared to the oceans, and the annual amount entering soil is significantly higher (Horton et al., 2017). Microplastics enter our soil through various means, including sewage sludge used for fertilizer (Corradini et al., 2019; Li et al., 2018), wastewater irrigation (Zhang and Liu, 2018), and plastic mulching used in agriculture (Huang et al., 2020).

The use of sewage sludge is a major contributor, with Europe alone estimated to add up to 125,850 tonnes of microplastics to agricultural soil per million inhabitants annually (Nizzetto et al., 2016). In fact, some studies suggest that agricultural lands in Europe and North America receive more microplastics from biosolids (between 63,000 and 430,000 tonnes annually) than the total amount of microplastics entering the world's oceans (93,236 thousand tonnes) (Nizzetto et al., 2016). (Figure 1).

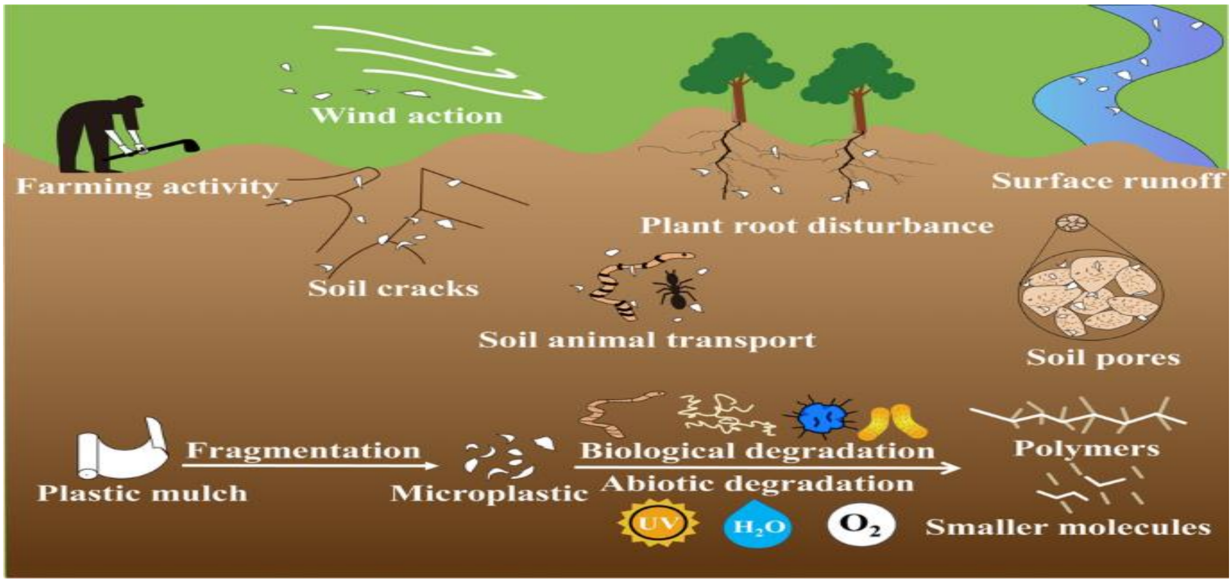

Figure 1. Current situation and ecological effects of microplastic pollution in soil (Zhang et al., 2022).

Microplastics are minuscule plastic fragments plaguing our soil. These invaders come from various sources, breaking down from larger plastic waste over time. This "plastic pollution" is a growing environmental concern as plastic slowly decomposes.

Agriculture, unfortunately, can be a culprit. Plastic covers used in greenhouses, films for mulching, and even irrigation pipes can degrade into microplastics over time. Additionally, plastic additives in fertilizers and chemicals can contribute to the problem as they mix into the soil.

Industrial activities are another source. Plastic granules and particles used during production, processing, and packaging can escape from factories and accumulate in the soil, adding to the microplastic burden. In essence, our reliance on plastic creates a hidden threat beneath our feet – microplastics in the soil.

3. Formation and properties of MPs in soil

Scientists are diligently investigating the existence, types, shapes, and origins of microplastics (MPs) in a wide range of soil environments around the world. This includes agricultural land, forests, grasslands, home gardens, residential and industrial areas, floodplains, wetlands, beaches, deserts, and more. These studies are revealing a disturbing truth: microplastics are prevalent in soils worldwide, particularly in agricultural areas.

The concentration of microplastics in soil can vary greatly, with some studies finding just a few particles while others report tens of thousands per kilogram (Zhang and Liu, 2018) (Figure 2).

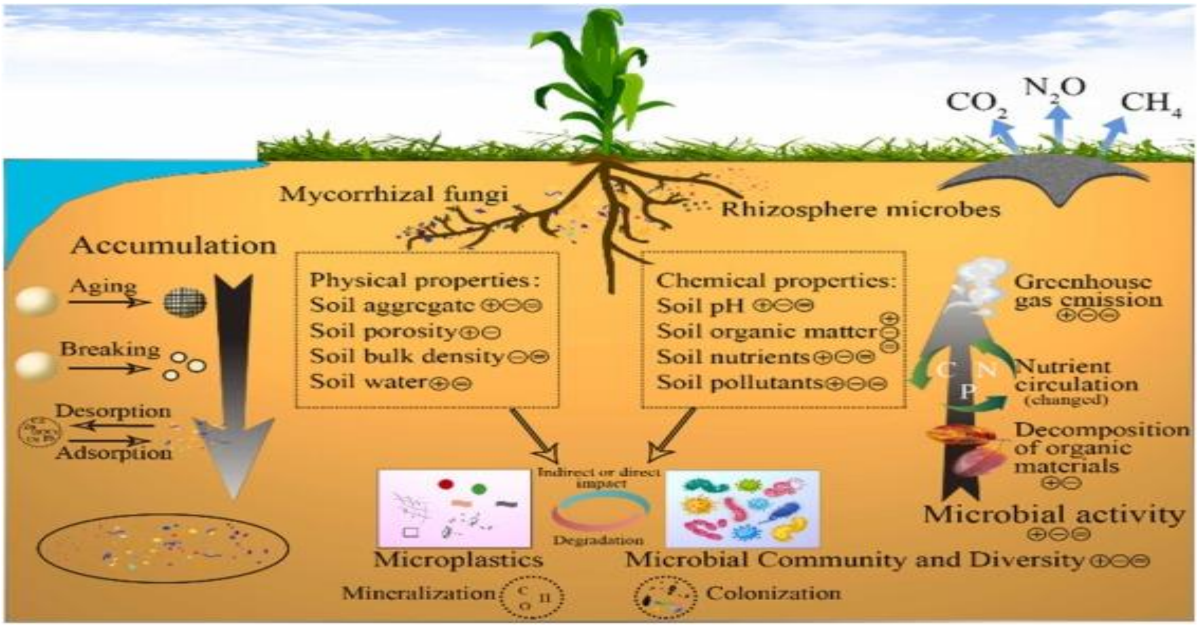

Figure 2. Effects of microplastics on soil properties (Wang et al., 2022).

Our everyday plastic use, from packaging to clothing, is creating a hidden threat – microplastics in soil. These microplastics are formed when larger plastic waste breaks down over time. The culprit? The very nature of plastic – it's incredibly durable and slow to degrade. Several factors accelerate this breakdown: sunlight, temperature changes, physical wear and tear, and even microbes. These fragmented bits of plastic, typically smaller than 5 millimeters, can then be carried by wind or water to land on the soil surface.

Because they're so small, microplastics can easily move through soil and even be accidentally ingested by organisms living there. This can harm these organisms and disrupt the overall health of the soil ecosystem. Microplastics also contribute to soil and water pollution. The answer? Reducing plastic waste and implementing better waste management practices are critical steps to prevent the formation and spread of microplastics in soil (Figure 2).

Beyond their size and shape, scientists are also studying the surface features of microplastics. Research shows that microplastics from different sources can have distinct surface textures, including scratches, wrinkles, and tiny pits. These features are likely caused by a combination of factors – physical wear and tear from rubbing against other particles, sun exposure breaking down the plastic, and even interactions with animals. Additionally, studies have observed signs of fungal growth and bacteria on the surface of microplastics, suggesting these tiny invaders are subject to further breakdown by biological processes in the soil.

4. Effects of microplastics on soil health

Microplastics don't just sit idly in soil; they can disrupt various aspects of its health. These tiny invaders can affect the soil's pH, structure, fertility, nutrient levels, populations of microbes, and even the stability of water-resistant clumps of soil particles (known as aggregates) (de Souza Machado et al., 2019). Microplastics can integrate into these aggregates in different ways. Fibrous microplastics tend to bind more tightly, while fragments become more dispersed (Guo et al., 2020). These aggregates are crucial for healthy soil structure as they provide homes for a variety of organisms (Rillig and Lehmann, 2020). Additionally, they influence how well air and water move through the soil, which is essential for microbial activity (Rillig et al., 2017; Rillig and Lehmann, 2020; Kayıkcıoglu and Okur, 2020). The presence of microplastics can actually decrease the overall density of the soil, which can have a ripple effect on the entire soil system (Figure 3).

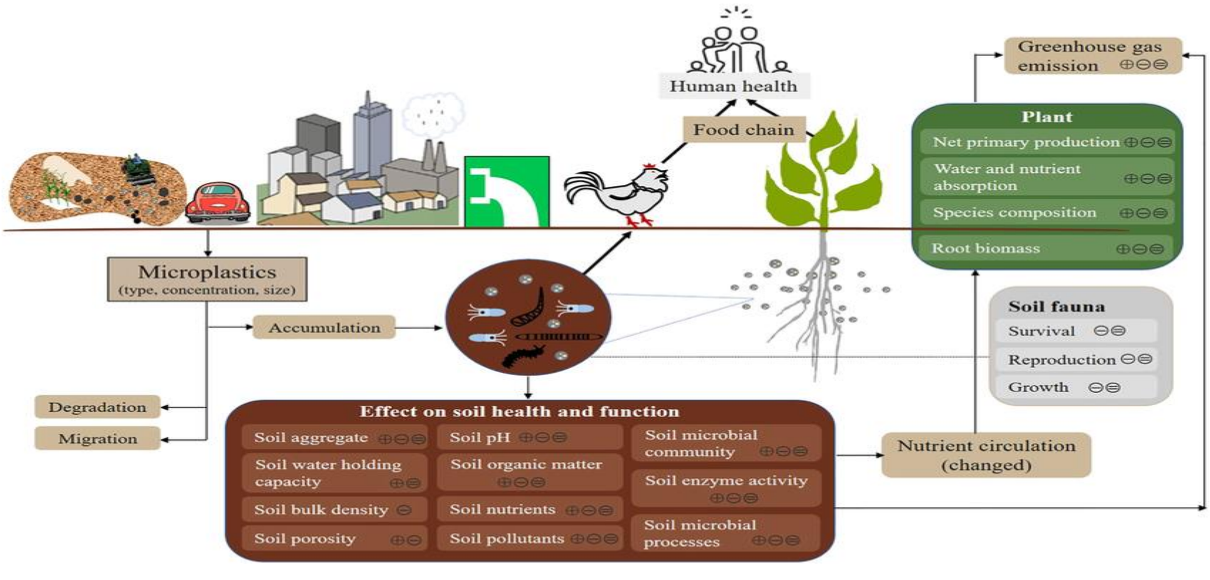

Figure 3. Effect on soil health and function (Yu et al., 2022).

The presence of microplastics in soil is a growing environmental and ecological concern. These tiny plastic invaders can disrupt soil health in several ways. First, they can wreak havoc on the soil's physical structure (Goa et al., 2022). Microplastics can weaken the stability of soil aggregates, the clumps of particles that create spaces for air and water to move through the soil. This reduced permeability can stifle plant root growth and hinder the soil's ability to retain nutrients. Microplastics can also disrupt the soil's chemical makeup. Studies suggest they can alter soil pH, leading to imbalances that affect how readily plants can access nutrients (Zhou et al., 2021). This can hinder plant growth and overall soil fertility.

Furthermore, microplastics are persistent in soil, accumulating over time. This can lead to a long-term decline in soil quality and potentially destabilize entire ecosystems. Soil health also relies on a thriving population of microbes. Unfortunately, microplastics can disrupt microbial activity, reducing the diversity of these organisms and impacting their habitats. This disrupts the delicate balance within the soil ecosystem, hindering its ability to function properly.

5. Impact of microplastics on soil carbon

Microplastics are like hidden hitchhikers in soil. Made mostly of carbon (Rillig and Lehmann, 2020), they often sneak into clumps of organic matter within the soil. While they blend in, current methods for measuring soil organic carbon can still detect them (Rillig, 2018). This infiltration introduces a new source of carbon into the soil system, one that doesn't rely on plants (net primary production). Because microplastics are essentially inert polymers, the carbon they contain breaks down very slowly (Rillig and Bonkowski, 2018). However, the rate at which this microplastic carbon enters the soil is still unclear.

Most research on microplastics has focused on their origins, physical properties, and chemical makeup rather than their carbon contribution (Rillig and Lehmann, 2020). The bottom line: the carbon in microplastics comes from fossil fuels. Since it's resistant to decomposition, microplastic carbon can accumulate in the soil. This raises a critical question: how do we account for this microplastic carbon when measuring soil's ability to store carbon, a vital function of healthy soil systems (Rillig, 2018; Rillig and Lehmann, 2020) (Figure 4). Microplastics may be adding carbon, but is it a sustainable source for the soil?

Healthy soil acts like a carbon bank, storing carbon through processes like organic matter accumulation and interactions with minerals. However, microplastic infiltration throws a wrench in this system. These tiny invaders can disrupt soil structure, water retention, microbial activity, and nutrient cycling. While they don't directly affect carbon storage, these changes can indirectly impact how quickly organic matter decomposes and how stable the stored carbon is in the soil (Çelik et al., 2023).

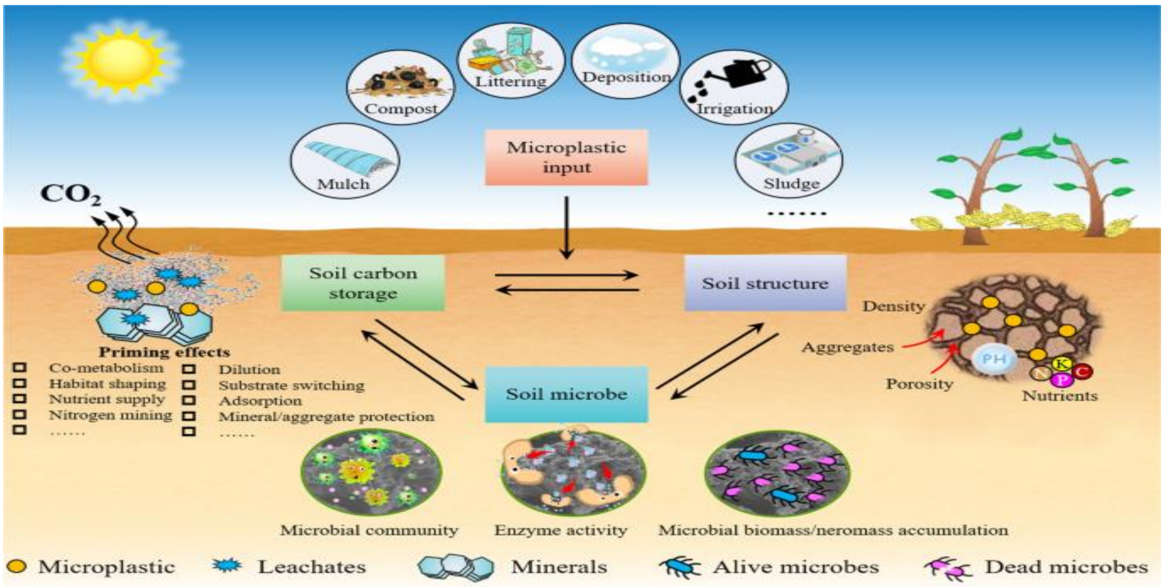

Figure 4. Effects of microplastics on soil carbon pool and terrestrial plant performance (Chen et al., 2024)

6. Impacts of MPs on soil fauna

Soil fauna, such as ants and earthworms, play a crucial role in the movement of microplastics (MPs) within soil ecosystems. Robins and Robins (2011) observed that ground-nesting omnivorous ants can randomly bury artificial plastics larger than 1 mm. Earthworms, meanwhile, facilitate the transport of MPs into deeper soil layers through various mechanisms.

Research by Huerta Lwanga et al. (2017) and Rillig et al. (2017) demonstrated that earthworms ingest MPs from the soil surface and move them to lower soil layers. This process of digestion and transportation, described by Yu et al. (2019) and Rillig et al. (2017), promotes the migration of especially smaller MPs into deeper soil strata.

The mechanisms behind this migration include the creation of earthworm burrows, which enhance the preferential infiltration of MPs into the deeper soil. Additionally, the casting activity of earthworms, as noted by Huerta Lwanga et al. (2017), contributes to moving MPs from the surface into their burrows. Overall, the activities of soil fauna, particularly ants and earthworms, are vital in the redistribution of MPs within soil ecosystems, affecting their distribution and potential environmental impacts.

7. Bioaccumulation of microplastics

This includes earthworms (Huerta Lwanga et al., 2016, 2017; Rodriguez-Seijo et al., 2017; J. Wang et al., 2019), nematodes (Fueser et al., 2019; Kiyama et al., 2012), snails (Panebianco et al., 2019; Y. Song et al., 2019), and even soil protozoa (Rillig and Bonkowski, 2018). A recent study using fluorescence imaging with Nile Red provided clear evidence that earthworms (Eisenia fetida) ingest both polyethylene (PE) and polystyrene (PS) MPs (Wang et al., 2019).

For instance, Lei, Wu et al. (2018) used fluorescently labeled PS MPs to track their distribution in the nematode Caenorhabditis elegans. They found MPs throughout the digestive system, from the beginning (pharyngeal lumen) to the end (rectum). Similarly, Baeza et al. (2020) observed MPs in all parts of earthworms after a 48-hour exposure, including the crop-gizzard, foregut, midgut, hindgut, and rectum. Studies on snails by Panebianco et al. (2019) also detected MPs in three edible species (Helix aperta, H. aspersa, and H. pomatia). Research by Huerta Lwanga et al. (2017) suggests this is how MPs enter and build up in soil fauna. Once inside the organism, these MPs can cause harm, including damage to the intestines. Furthermore, there's a potential risk to animal and human health if MPs bioaccumulate and move up the food chain. However, Fueser et al. (2020) found that nematodes completely consumed PS MPs within an hour, with a very low bioconcentration factor. This suggests the impact of ingestion and bioaccumulation might vary depending on factors like feeding behavior, diet, exposure duration, MP size, and dose. Clearly, more research is needed to fully understand this complex phenomenon.

8. Transport of microplastics into soil

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Conclusions

The widespread presence of microplastics (MPs) in soil ecosystems presents numerous and complex threats to soil health, biodiversity, and overall ecosystem functioning. Microplastics interact directly with soil organisms, leading to physical damage, disruption of biological processes, and acting as carriers for harmful chemicals and pathogens. These interactions can destabilize soil food webs and reduce the resilience of terrestrial ecosystems.

Beyond their impact on soil organisms, MPs also affect crucial enzymatic activities essential for nutrient cycling, organic matter decomposition, and maintaining soil fertility. MPs can adsorb enzymes and inhibit biochemical processes, disrupting nutrient dynamics, altering soil biogeochemistry, and diminishing the soil's ability to support plant growth and productivity.

Furthermore, as soil organisms facilitate the vertical movement of MPs into deeper layers, this transport within the soil matrix exacerbates their negative effects. This movement not only increases the exposure of soil life to MPs but also prolongs their presence in the environment, heightening the risk of long-term ecological harm.

The ongoing accumulation of MPs in soil ecosystems leads to risks that extend well beyond immediate ecological impacts. As MPs persist in soil, they can alter its physical properties, disrupt interactions among living organisms, and undermine the resilience of ecosystems to environmental stressors. These changes can significantly impact soil structure, microbial communities, and plant-soil interactions with far-reaching consequences for the sustainability of terrestrial ecosystems.

Given these findings, urgent actions are necessary to mitigate the negative effects of MPs on soil health and biodiversity. Addressing MP pollution in soils requires strategies such as reducing plastic waste at its source, improving waste management practices, and developing innovative remediation technologies tailored to soil environments. Tackling the challenges posed by MP pollution is crucial for restoring and maintaining healthy, resilient terrestrial ecosystems for future generations.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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To Cite: Sakin, E., Dilekoğlu, M.F., Yanardağ, İ.H., Çelik, A., 2024. The Unseen Threat: The Devastating Impact of Microplastics on Soil Health; A mini Review. *MAS Journal of Applied Sciences*, 9(3): 552–563.
DOI: http://dx.doi.org/10.5281/zenodo.13293398.