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Soil Microplastic Pollution and its Remediation: An Overview

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THE GLOBAL annual production of plastics increases year by year. The problem of plastic pollution comes from using plastic in virtually all our life activities. Thus, plastic pollution affects freshwater, marine, and terrestrial ecosystems. Microplastics have received considerable attention in aquatic ecosystems, but much less in the soil ecosystem. The use of plastic in agriculture is called agri-plastics and is used as an alternative to glass, paper, and mulch to achieve better crop yields and quality. Microplastic results from breaking plastic into small pieces (<5 mm) and can come from many different sources. Soil pollution by microplastics has been reported to negatively affect the soil microbial community, pollute groundwater, and have both direct and indirect toxic effects on humans and the food chain. The environmental fate of plastics and risks of plastic degradation products in soil is discussed. Remediation of microplastics includes physical, chemical and biological approaches. The best remediation approaches depend on the microplastic's origin, polymer composition, particle size, and shape. Microplastics in soil are still poorly understood and needs more investigation. This review specifically focuses on the environmental fate of degradation products and non-polymeric additives released from plastics, a topic that remains underexplored in current literature.

Keywords: Alkylphenols, Biodegradation, Heavy metals, Nano-plastics, Phthalates, Soil ecotoxicity, Soil and human health.

1. Introduction

Soil pollution is an ancient problem (Ibáñez et al 2015) and is one of the most important modern global issues that poses a risk human and ecosystem health. Soil pollution is mainly linked to anthropogenic activities, leading to the accumulation of pollutants in soils (Li et al. 2024). Soil pollution is associated with mining, waste disposal, agrochemical, industrial, and military activities (Brevik et al. 2020; Elumalai et al. 2025). Soil pollution can lead to a loss of soil organic carbon and nutrients, nutrient antagonism, degradation of soil structure and increased soil erodibility, and deterioration of terrestrial ecosystems along with the food chain. Among soil pollutants, microplastics are an area of worldwide concern.

Microplastics anthropogenically formulated organic compounds that are now abundant in natural environments have a persistent presence due to the difficulty of degrading them, and they may endanger human health (Feng et al. 2023; Cao et al. 2024). The risks of soil pollution by microplastics may include reducing the soil microbial network complexity (Shi et al. 2022; Liang et al. 2023; Maguire and Gardner 2023), soil biodiversity loss (Hu et al. 2023), pollution of groundwater (Yu et al. 2025), and both direct and indirect toxic effects on humans and the food chain (Mamun et al. 2023; Carvalho et al. 2024; Mir et al. 2025). Microplastics in soil and terrestrial ecosystems need additional study of their impacts, migration, and remediation (Wang et al. 2020; Elbasiouny et al. 2022; Surendran et al. 2023). Furthermore, the analytical detection of microplastics in soil-plant systems is still considered a significant challenge (Azeem et al. 2023).

Therefore, this mini-review highlights soil microplastic pollution with a focus on the sources, risks, and different pathways of microplastics degradation in soils. Remediation approaches for microplastics will also be discussed.

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2. Microplastics: sources and risks

The spread of microplastics is a potential threat that poses risks to ecosystems that are still poorly understood. The main sources of microplastic pollution and potential environmental risks are summarized in **Table 1**. Sources of plastic pollution vary from landfills, biosolids, and sewage sludge to synthetic fibers from textiles and clothing, physical degradation of plastics, agricultural plastic film and mulch residues, household solid wastes, tire abrasion, organic fertilizers, plastic pellets, personal care products, and paint, leading to the widespread presence of microplastics in the environment (**Figure 1**; Arias et al. 2023; Athulya et al. 2024; Galarpe et al. 2021; Goukeh et al. 2025; Sait et al. 2021; Turner et al. 2022; Xiao et al. 2024; Xu et al. 2025). The risks posed by these fine particles are numerous, ranging from their intrinsic toxicity to their ability to carry other harmful pollutants, direct impact on ecosystems and, consequently, human health. Potential microplastic pollution sources and risks, highlighting the complex relationship between activities and ecosystems, are illustrated in **Figure 2.** In many ways the presence of microplastics in groundwater and soil is a silent threat.

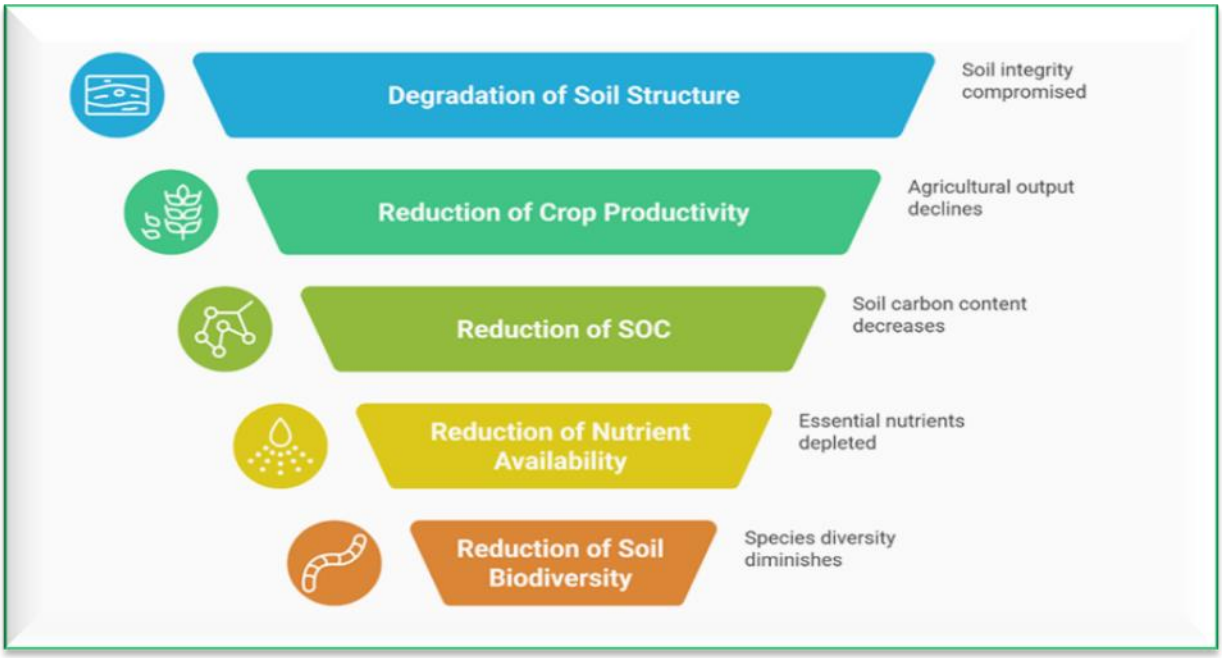

Fig. 1. Different degradation processes in soil due to microplastic pollution (adapted from FAO and UNEP 2021).

Table 1. Sources of microplastic pollution and risks.

Sources	Risks	References
Biosolids and sewage sludge	Accumulation of toxic pollutants such as heavy metals and pesticides with microplastics.	Mohajerani and Karabatak, (2020)
Synthetic fibers from textiles and clothing	Microfibers are transferred to plants and then to humans through the food chain.	Acharya *et al.* (2021)
Physical decomposition of plastic	Intrinsic toxicity from plastic additives.	Beiras *et al.* (2021)
Agricultural plastic film residues (such as plastic mulch)	Deterioration of soil biological, chemical, and physical properties (e.g., microbial abundance and diversity, nutrient cycling and availability, bulk density, and water holding capacity)	Koskei *et al.* (2021)
Household solid waste (*e.g.*, landfills)	Negative impact on the biodiversity of microorganisms and animals in the soil.	Anunobi (2022)
Cosmetics and personal care products	Direct and indirect toxic effects on humans and plants.	Losetty *et al.* (2024)
Industrial waste and air emissions	Groundwater pollution and the transfer of microplastics to rivers and seas.	Hoang *et al.* (2025)
Physical decomposition of plastic	Intrinsic toxicity from plastic additives, increase in plastic surface area leading to enhanced chemical impacts.	Beiras *et al.* (2021)

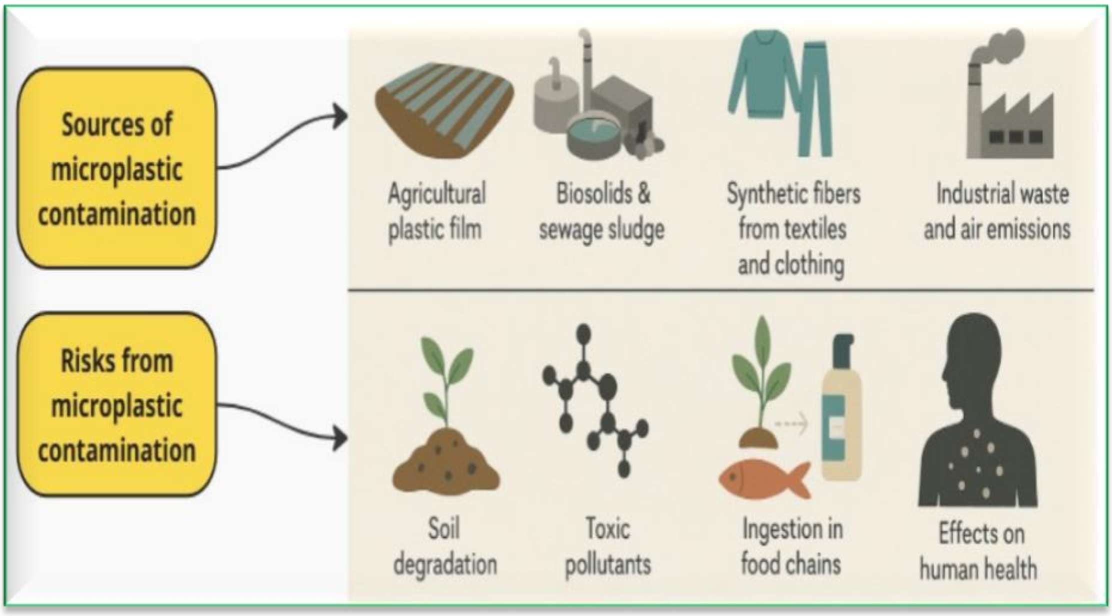

Fig. 2. Sources of microplastic contamination and risks.

Microplastics are common in different environmental compartments (i.e., air, soil, water). This widespread distribution of microplastics along with their environmental persistence makes identifying microplastic sources and pathways of movement in the environment a significant challenge for researchers and resource managers (**Figure 3**). There is an urgent need for better understanding of the relative contributions and characteristics of different microplastic sources, their pathways of movement through the environment, and the factors affecting the fate of microplastic particles in the environment to inform policy and mitigation strategies (USGS 2023). The following issues are important for a better understanding of microplastics: (1) environmental sources, pathways, and fate, (2) human and wildlife exposure routes, (3) ecotoxicology, (4) sampling protocols, (5), analytical methods, and (6) interdisciplinary science to support microplastic research (USGS 2024).

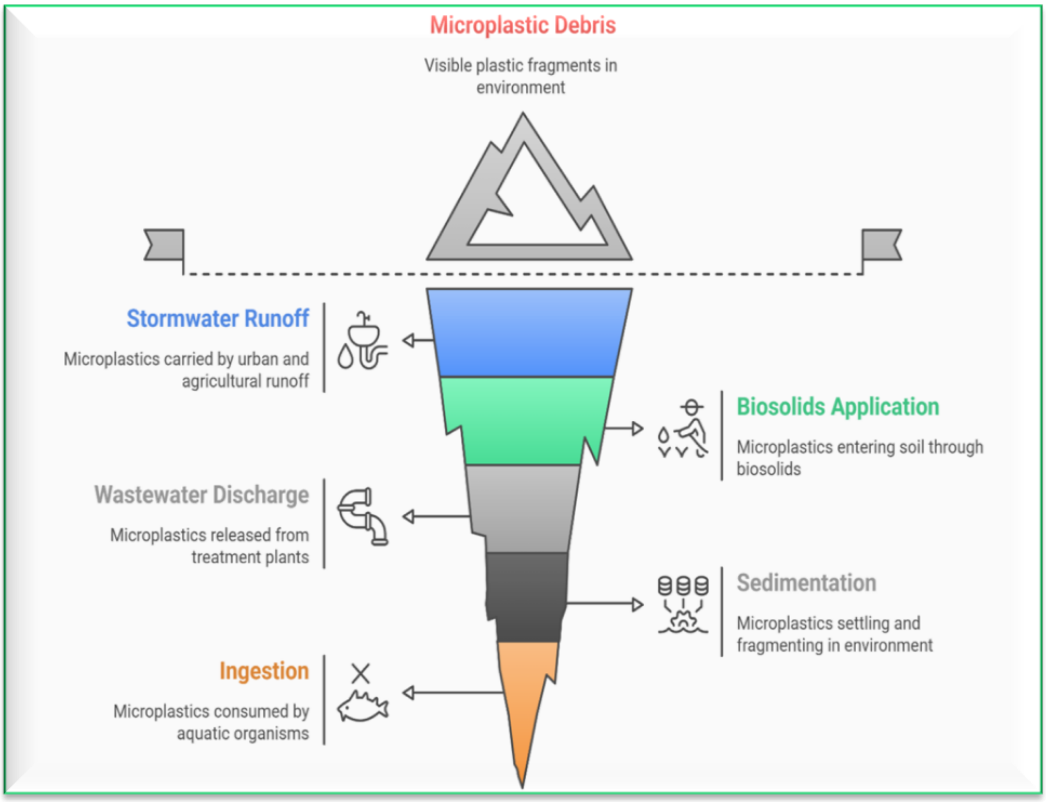

Fig. 3. Microplastics Sources, Pathways and Fate Conceptual Diagram.

adapted Source: https://www.usgs.gov/media/images/microplastics-sources-pathways-and-fate-conceptual-diagram. Accessed on 24.05.2025

Several reports have discussed the potential risks of microplastics in different environments and organisms, such as freshwater ecosystems (Jaiswal et al. 2025; Li et al. 2025), sediments (Yin et al. 2023), aquatic organisms (Li et al. 2025), air (Zhang et al. 2025), human health (Winiarska et al. 2024), and soil and the food chain (Li et al. 2023). The most common risks of microplastics in soil may include risks to living organisms and integration into the human food chain (Li et al. 2023). These risks vary from one ecosystem to another with significant impact on agroecosystems, ecology, human health, and overall quality of life (Shetty et al., 2023). Exposure to microplastic particles is associated with human cardiovascular conditions and chronic respiratory diseases (Sakthivel et al., 2024). Anthropogenic activity may increase soil microplastics pollution, with the exact impacts depending on duration of exposure and soil type, with particular impacts on soil nutrient cycling and food production along with soil microbial communities (Bodor et al. 2024).

3. Environmental Fate and Risks of Plastic Degradation Products in Soil

Plastic degradation in terrestrial environments results in the formation of microplastics and the release of chemical additives, both of which pose substantial threats to soil ecosystems. These byproducts can alter soil physicochemical properties, disrupt microbial community, and interfere with plant physiology, leading to bioaccumulation across food webs and ultimately threatening ecological and agricultural sustainability (Kumar 2023). A survey of the degradation of plastic in soil under different conditions is provided in **Table 2.** It is estimated that annual global production of plastics reached 391 million tons in 2021, with agri-plastic use at 6.6 million tons per year (2024). Plastic production is expected to increase about 64% by 2030 (Campanale et al. 2024). Global production of biodegradable plastics was 2.18 million tons in 2023 and is expected to increase to 7.43 million tons by 2028 (Liu et al. 2024). Plastic mulch film is one of the major contributors to macro- and microplastic pollution in agricultural fields, with global use at 2.5 million tons per year (Graf et al. 2025). Degradation of conventional and biodegradable plastics in soil is controlled by many environmental factors including soil moisture, pH, and temperature. Soil microorganisms are the main players in the degradation of plastic polymers through hydrolysis of polymers, microbial extracellular enzymes, and migration of polymer chains. In general, **bacterial degradation** is favored under neutral to alkaline soil conditions, as acidic environments tend to inhibit bacterial growth and reduce biodegradation efficiency. (Liu et al. 2024) In contrast, **fungal degradation** can remain active under mildly acidic conditions. Some studies have shown that maximum enzyme activity for *Penicillium chrysogenum* and *Aspergillus niger* was reached at pH 5 and 6, respectively, suggesting that certain fungi are well-adapted to acidic environments and may play a key role in biodegradation when bacterial activity is limited (Zade et al 2023).

Degradation of conventional and biodegradable plastics in soil is controlled by many environmental factors including soil moisture, pH, and temperature. Soil microorganisms are the main players in the degradation of plastic polymers through hydrolysis of polymers, microbial extracellular enzymes, and migration of polymer chains. In general, acidic soil conditions inhibit bacterial growth and reduce biodegradation efficiency, whereas neutral and alkaline soils exhibit the highest biodegradation rate (Liu et al. 2024). Microbial degradation, solar UV, rain, irrigation, wind, and farming activities are all important in the degradation of agricultural plastics (Qiang et al. 2023). Polyethylene microplastic biodegradation in the soil includes three steps (1) colonization of the film surface by polyethylene-degrading microorganisms, (2) secretion of extracellular oxidases for depolymerization of the plastic film by enzymes, and (3) microorganism uptake and utilization of monomers and short oligomers of oxidation products for energy production and biomass formation with CO_2 release (**Figure 4;** Qiang et al. 2023).

3.1. Nanoplastic Generation and Plant Uptake

Nanoplastics defined as particles smaller than 100 nanometers, are formed through the progressive mechanical, chemical, and biological breakdown of microplastics in the soil (Kwa and An 2021). Their nanoscale size enhances mobility and bioavailability, increasing their likelihood of interaction with plants and microorganisms. Recent studies reported that nanoplastics can be absorbed by plant roots and translocated to aerial tissues. For example, in rice (*Oryza sativa* L.) continuous exposure to nano-polyethylene terephthalate (nPET) at concentrations of 10 mg L^{-1} significantly reduced grain yield by 21–34%. This exposure also impaired metal homeostasis (notably Fe, Zn, and Cu) and altered the structure and function of the rhizosphere microbiome, which plays a significant role in nutrient cycling (Xie et al., 2025). Zhou et al. (2021) also reported that nanoplastics accumulated in plant vascular tissues, impairing photosynthesis and antioxidant enzyme activity. This bioaccumulation raises concerns about potential trophic transfer to herbivores and humans. Beyond plants, nanoplastics have also been shown to disrupt soil microbial communities. Hao et al. (2023) reported that NP exposure reduced bacterial diversity and selectively enriched plastic-degrading taxa. Algal populations displayed relatively greater resilience, potentially due to bacterial buffering effects. Nevertheless, the integrity of algae–bacteria interactions was compromised, leading to alterations in primary productivity and nutrient dynamics in macro-phyte-dominated systems. Hao et al. (2023) reported that nanoparticle (NP) exposure reduced bacterial diversity and selectively enriched for plastic-degrading taxa. They also observed that algal populations exhibited relatively greater resilience, potentially due to bacterial buffering effects. However, they noted that the integrity of algae–bacteria interactions was compromised, resulting in alterations in primary productivity and nutrient dynamics in macrophyte-dominated systems.

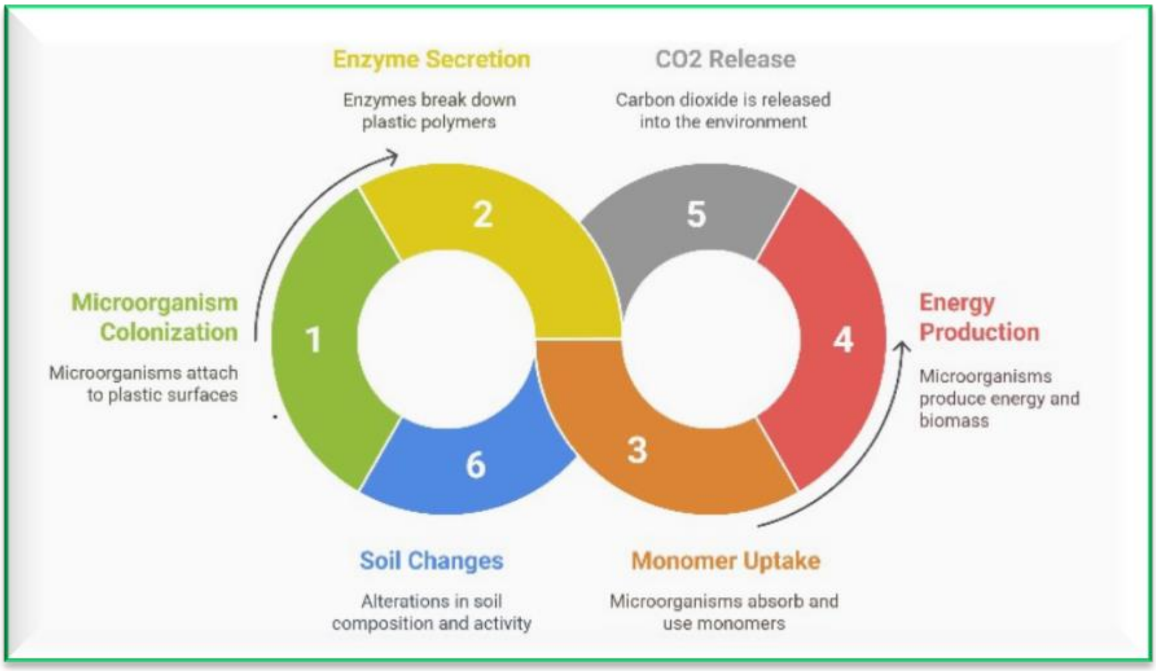

Fig. 4. Suggested mechanism of polyethylene microplastic biodegradation in the soil.

Table 2. Degradation of plastic in soil under different conditions.

Source of plastic	Soil conditions	Degradation conditions and details	References
Polyvinyl chloride (PVC) microplastics	Grassland (Chiltern; pH 7.3; WHC 73%; OM 16%) and an acidic heathland (Dorset; pH 3.8, WHC 41%; OM 3.7%) for 100 days	Diethyl hexyl terephthalate (DEHTP), with diameter of 3.9 mm; degradation was slower in acidic heathland than in grassland; DEHTP was released rapidly, with 6.6–12.1 ng DEHTP released per mg PVC within <2 h	Billings et al. (2025)
Two mulch film types: conventional LDPE and a biodegradable PLA/PBAT	Plastic mulch film edges were buried 10 cm into the soil under temperate oceanic climate conditions	UVA was the most suitable and realistic artificial degradation method at a medium rate (5 months), whereas UVC is recommended for rapid degradation	Graf et al. (2025)
Poly(butylene adipate-co-terephthalate) (PBAT)	Yellow-brown soil, organic carbon content 17.65 g/kg, soil organic nitrogen content 0.65 g/kg; pH 7.6, biodegradation for 180 days	PBAT microplastics initially increased to a peak before decreasing by 74.7 % within 180 days; predominant microplastics were film-shaped and smaller than 10 µm	Wang et al. (2025)
Plastic-laden landfill site	Soil sampling (30-120 cm), pH 7.25 – 11.50; bulk density 1.25-2.32 g cm^{-3}, biodegradation for 6 months	Both fungi and bacteria forming clusters were effective in biodegradation of plastics through enzymatic pathways	Kumar et al. (2024)
Low-density polyethylene (LDPE) mulch film	Incubation of soil after using plastic film for 15 years	Degradation measured as weight loss was up to 40% after 30 days by the bacteria *Burkholderia cepacia*, *B. diffusa*, *B. aenigmatica*, and *Chrysebacterium nepalense*	Lin et al. (2024)
Biodegradable plastics, PCL & PBS	Fertilized soil with application of vermicompost	In fertilized soil, PCL and PBS required 4 to 6-months for complete degradation	Lee et al. (2024)
5 soil-biodegradable plastic mulches	Soil: silt loam, pH 6.2 and organic matter content 2.8%	The degradation rate was 90% during a period up to 2 years	Griffin-LaHue et al. (2022)
Polyethylene (PE) films	Soil: pH 7.8, soil organic matter 6.18 g/kg, and available potassium 102.3 mg/kg	Degradation of PE-films can change the soil microbial community composition and hold the post of unique matrix for microbial colonization by creating a specialized habitat for microbes	Huang et al. (2021)

PLA: degradable polymers (e.g., poly(lactic acid); PBAT: poly(butylene adipate-*co*-terephthalate); PCL: polycaprolactone; PBS: poly(butylene succinate; LDPE: low-density polyethylene; UVA: ultraviolet A radiation; UVC: ultraviolet-C radiation

3.2. Additive Leaching and Soil Ecotoxicity

In parallel with nanoplastic formation, plastic degradation leads to the leaching of various chemical additives into the soil, including phthalates, flame retardants, heavy metals, alkylphenols, and ultraviolet (UV) stabilizers. These compounds are often persistent and biologically active, posing ecotoxicological risks to both soil organisms and overall ecosystem functioning. Phthalates such as di-(2-ethylhexyl) phthalate (DEHP) are compounds commonly used as plasticizers in polyvinyl chloride (PVC) and other polymers. DEHP leaching into soil alters microbial respiration and reduces enzyme activity. Li et al. (2024) demonstrated that exposure to DEHP in a microcosm experiment led to DNA damage, mitochondrial dysfunction, and reduced the diversity of earthworm gut microbiota, in addition to shifts in keystone microbial taxa. Polybrominated diphenyl ethers (PBDEs) used as flame retardants in electronic devices, textiles, and building materials can leach from plastic waste into the environment. PBDEs (e.g., BDE-209 and BDE-47) exhibit strong bioaccumulation in terrestrial and aquatic organisms. Although most toxicological studies have been conducted in aquatic environments, their findings remain relevant to terrestrial systems. For example, Li et al. (2023) reported that PBDE bioaccumulation in aquatic organisms varied by species and diet, though consumer health risks were generally below harmful thresholds. These compounds can enter soil through contaminated water used for irrigation, sediment deposition, or land application of biosolids. Chronic PBDE exposure has been linked to hepatotoxicity, thyroid hormone disruption, and neurotoxicity (Mensah et al., 2022; Wang et al., 2023), raising concerns about their long-term effects on soil biota and human health through food production systems.

Heavy metals also leach from certain plastics, particularly colored microplastics containing cadmium-based pigments. Liu et al. (2024) found that cadmium ions (Cd^{2+}) released from colored polystyrene particles under sunlight increased 40-fold for particles smaller than 0.15 mm, contributing to soil contamination and plant toxicity. Alkylphenols, e.g., nonylphenol, are another class of additives with significant environmental impact. These endocrine-disrupting compounds (EDCs) are known for their estrogenic activity. Gałązka and Jankiewicz (2022) reported that alkylphenols persist in over 70% of treated effluents and pose chronic risks to aquatic life at concentrations as low as nanograms per liter. These findings have important implications for soil ecosystems, as treated wastewater is increasingly used for agricultural irrigation, especially in water-scarce regions. Moreover, alkylphenols can enter soil environments through land application of sewage sludge or leaching from contaminated surface waters into adjacent soils. In soil, nonylphenol has been shown to alter microbial community composition by increasing the abundance of heterotrophic and oligotrophic microbes while reducing actinomycetes (Kuzikova et al., 2019). Proteobacteria often become dominant, with Gammaproteobacteria and Alphaproteobacteria particularly active in degradation pathways (Wang et al., 2015). Functionally, nonylphenol exposure can suppress nitrogen mineralization and immobilization, although certain microbial taxa may enhance its biodegradation through adaptive metabolic pathways (Chen et al., 2024).

Another concerning group of additives includes benzotriazole-based UV stabilizers (BUVSs), such as UV-328. These compounds are used in protection of plastics from photodegradation but persist in soil for extended periods, with reported half-lives ranging from 75 to 345 days (Lai et al., 2014). BUVSs accumulate in biosolid-amended soils and interfere with microbial growth and metabolism. Jia et al. (2006) reported that BUVSs reduce microbial growth yields and act as metabolic uncouplers, decreasing efficiency in substrate utilization. Their long-term toxicity causes a risk not only to microbial community structure and function but also to broader processes such as organic matter decomposition and nutrient cycling (Cantwell et al., 2015). While some studies suggest microbial adaptation to BUVS exposure, their persistence and potential for bioaccumulation continue to raise serious ecological concerns (Chen et al., 2024). The effects of microplastic degradation products on the soil system are depicted in **Figure 5.**

4. Microplastic remediation approaches

The widespread occurrence of MPs pollution necessitates the development of targeted remediation strategies specifically designed for agroecosystems (Tayyab et al., 2024). The challenges associated with MPs pollution result from the complicated connections among their physicochemical characteristics, interactions with microorganisms and other pollutants, aging-related changes in their properties, and their small sizes, which allow them to spread and move between environmental compartments and increase their ubiquity (Nohara et al., 2024). Thus, reliable technology must be utilized to remove MPs from soil because their prevalence has grown recently and they pose serious health risks to humans and other living things (Ali et al., 2024). Microplastic's origin, polymer composition, particle size, and shape are critical factors that should be considered when developing different microplastic remediation methods (Nohara et al., 2024). The remediation of plastic waste may be accomplished in two ways: 1) upstream, involving wastewater treatment plants, bioplastics, and waste management, and 2) downstream, involving physiochemical and biological remediation (Ali et al., 2024). Chellasamy et al. (2022) reported that the remediation of MPs involves two fundamental methods: separation and degradation. They can be classified as physical, chemical, and bioremediation technologies. Although numerous physical, chemical, and biological techniques are being studied for removal of MPs, a few demonstrated high effectiveness in laboratory settings. These methods also come with some limitations regarding environmental conditions. Physical and chemicals methods have advantages and disadvantages (Badola et al., 2021, Elbasiouny and Elbehiry, 2023). Due to their disadvantages and the growing spread of soil MPs pollution, it is indispensable to identify efficient and sustainable amendment agents for MPs remediation from soil (Raun et al., 2024; Liu et al., 2025).

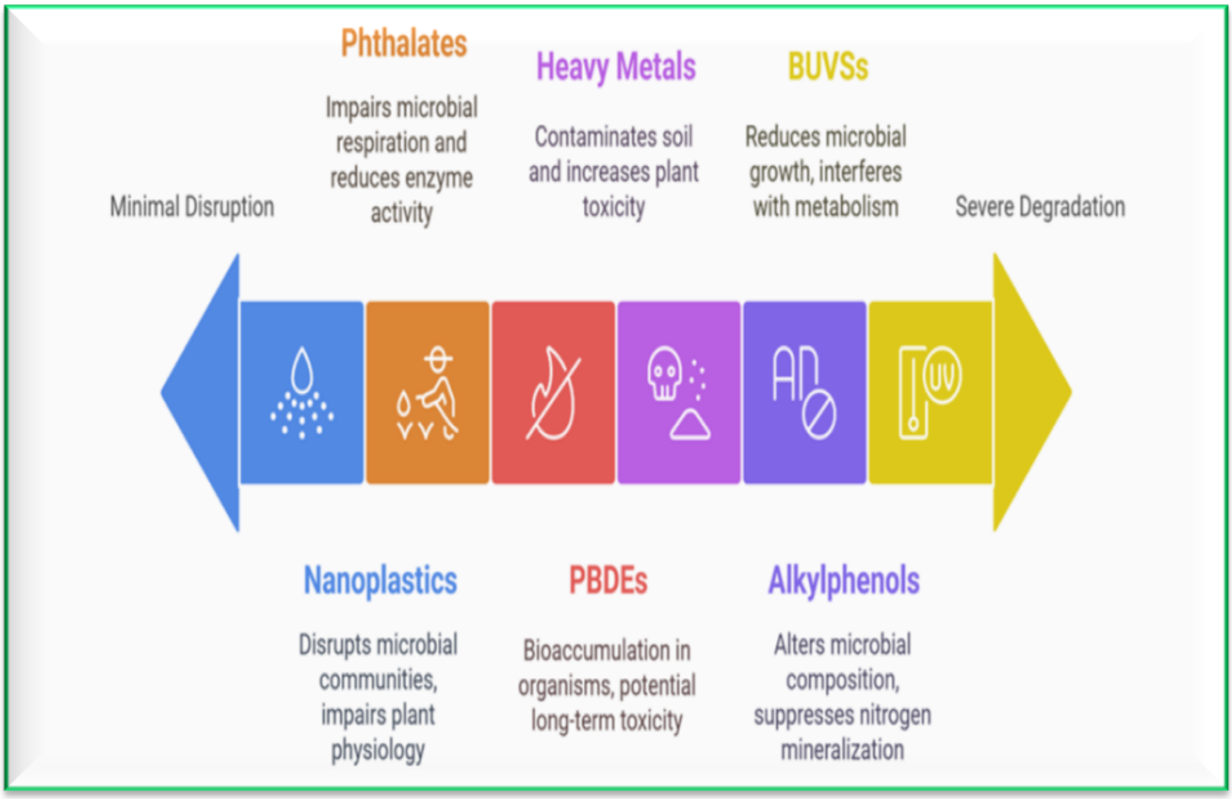

Fig. 5. Impact of microplastic degradation byproducts on the soil ecosystem.

4.1. Physical and chemical remediation of microplastics in soil

MPs are challenging to separate from soil because of their chemical stability. The primary strategies to decrease MPs pollution are reducing their discharge and encouraging in-situ degradation. The yearly input of MPs into farmland soil alone exceeds the entire quantity of MPs imported into marine water globally, and the overall amount of MPs in the soil is 4–23 times larger than that in marine habitats (Wang et al., 2023). Soil MPs can be separated and degraded using a variety of physical, chemical, and biological processes. However, due to the complexity and variability of the soil environment, the majority of the approaches are still at the stage of laboratory testing. The efficiency of these methods is hampered by the absence of a thorough examination of the origins, distribution, transport, and transformation mechanisms of soil MPs, as well as the factors that influence soil MPs contamination in various locations. Furthermore, MPs' screening, separation, and degrading techniques still lack maturity and accuracy, which lessens the significance of their use at polluted locations (Xu et al., 2025a). Sedimentation and centrifugation are reported by Barai et al. (2025) as two density separation techniques to separate MPs from soi because MPs have a lower density than soil. MPs can settled or floated at varying rates to the surface by altering the density of the surrounding liquid. NaCl solution is generally considered an affordable and efficient salt for the MPs removal. It is stated that experiments performed on soil spiked with different MPs types resulted in over 95% plastic extraction. As MPs are less dense than soil particles, they tend to float in the water, allowing for separation by filtration. Thus, the filtration method is widely used for MPs removal. In addition, the flotation approach capitalizes on the buoyancy principle which can also be utilized in MPs removal from soil (Barai et al., 2025). Thus, all of these previous methods are performed at a laboratory scale not on a field scale and some of these methods have some disadvantages and will be highly costly or lead to other issues at the field scale which require other treatments. Yuan et al. (2024) reported that density-separation technique is inappropriate for large-scale plastics field flotation. They also added that most of the physical methods for MPs removal are applied in water or wastewater and some of these methods have some disadvantages such as filtration, where some larger particles can be filtrated while smaller ones can pass through the filter to water. As well, Although membrane bioreactor highly improved the MP removal efficiency, the contamination resulting from MPs may bring irreversible membrane fouling, affecting the sustainability of the performing of this technology. Physical approaches for MPs removal from soil require more research in the future because most of the physical methods were examined on water and wastewater or practically at the laboratory scale.

Chemical degradation (including thermal and oxidation degradation) plays a pivotal role in the recycling of plastic waste. Thermal degradation of plastics involves breaking down polymers into oligomers and monomers by absorbing heat under controlled circumstances, necessitating either high temperatures or extended heating. Oxidation process includes photochemical and electrochemical oxidation. To induce the photochemical oxidation of plastic, it is necessary to expose the polymer to sunlight with enough ultraviolet radiation to initiate the photodegradation process in plastics. The fundamental principle behind electrochemical oxidation is that reactive oxygen species produced by the anodic oxidation of water or other substances (such as H_2O_2, sulfate, persulfate, etc.) oxidize the polymer adjacent to the anode (Yuan et al., 2024). Chemical catalysis is a widely used method for degrading MPs. It encompasses using chemicals to break down MPs in soil; however, this remediation method has significantly diminished, likely due to its lower environmental friendliness as compared to photocatalysis and biocatalysis (Adamu et al., 2024). Du et al. (2021) mention Advanced oxidation processes (AOPs) is one of the most common approaches that are currently being used for MPs breakdown besides biological degradation. These two processes can break the chemical bonds that hold polymer MPs together, resulting in tiny molecules that can be further transformed into valuable chemicals or even fully mineralized into CO_2 and H_2O. MPs ultimately break down into accessible organic or inorganic compounds due to the irregular breaking of the polymer chain, which might happen at any monomer in the polymer. Certain MPs have a chain fracture near the end of the monomer repeating unit, followed by successive breaks in the remaining monomer due to chain depolymerization. Different polymer kinds have different breakdown mechanisms and products, which are greatly impacted by environmental variables. According to Xiang et al., (2023) the degradation of MPs can be accelerated by a sequence of physical and chemical reactions such as adsorption, APOs, and biodegradation. Nevertheless, these approaches have drawbacks. Photodegradation is an uncontrolled process. It is impossible to fully identify the sorts of intermediates in the photochemical system and the extent of photoaging, even in a lab setting. Moreover, photodegradation uses more power. Light pollution can also result from prolonged exposure to sunshine. Despite utilizing free solar energy, photocatalytic oxidation only partially degrades most polymers under UV light, and the degree of deterioration is insufficient. In addition to being difficult to recover, the catalyst that was introduced to the process has the potential to cause secondary pollution. Because of its excellent controllability, ease of use, and minimal secondary contamination, electrochemical oxidation offers a wide range of potential applications in the treatment of biodegradable polymers. However, it is challenging to regulate the reaction process for these activities, and it is unclear whether the intermediate compounds that are produced by their breakdown are hazardous or not. In this context, Yin et al. (2025) confirmed that there is an urgent need for new solutions because the physical, chemical, and microbiological remediation techniques now in use are insufficient for the large-scale, in situ removal of microplastics because of they high cost, high energy consumption, its limited application and possibility of secondary pollution

4.2. Phytoremediation and bioremediation of microplastic in soil

Phytoremediation uses plants and their associated soil microbes as a type of in-situ restoration method to reduce the levels of pollutants concentration such as MPs in the soil ecosystem (Thapliyal et al., 2024). The uptake and accumulation of MPs by plants is influenced by size, shape, surface charge, composition, and mechanical properties of the MPs. Microplastics, particularly very small particles, can penetrate through the nuclear membrane to enter the plant cell nucleus, disturbing the structural and functional characteristics of chromatin, as in faba bean (*Vicia faba*). Smaller MPs are taken up via endocytosis, as the diameter of endocytic vesicles is less than 200 nm. The most sensitive part for MP uptake in the plant is the root tips. However, MPs in the 0.2-200 μm size range can enter via crack-entry pathways in the lateral plant roots, such as seen in wheat (*Triticum aestivum*). Therefore MPs, particularly the smaller particles, are readily translocated due to their high bio-accessibility and bioavailability to the plant cell. The indications of translocation and phytoaccumulation of MPs in different plant parts suggest the removal of these contaminants from MP-polluted environments (Thapliyal et al., 2024). Thus, using hyper-accumulator plants for MPs phytoremediation is a simple, cost-effective and eco-friendly method, although it is still a relatively new approach (Rozman et al., 2023; Arif et al., 2024). However, Tang et al. (2023) reported that by adsorbing, trapping, and collecting MPs in their roots and tissues, plants can serve as temporary sinks for MPs. There is, however, little evidence that MPs are really broken down by plants. MPs may desorb or resuspend according to environmental variables, making plants possible MP suppliers. Concerns about ecotoxicity arise because accumulated MPs in plants may also make their way into the food chain. Additionally, MPs may harm plants' health and hinder their capacity to eliminate other contaminants. Because MP contamination is so pervasive, phytoremediation is not very useful unless it is properly coupled with bioremediation to promote MP breakdown.

Biodegradation is an effective approach to break down many types of toxic substances in the environment using various physical, chemical, and enzymatic activities facilitated by microorganisms (Ali et al., 2024). Microbial-mediated bioremediation is a promising strategy for MPs removal (Han et al., 2024). Microplastics are biologically fragmented via the cell membrane. While tiny monomers migrate inside microbial cells, larger monomers remain outside. The oxidation of these monomers in microbial cells creates energy which is utilized for biomass production. Microorganisms start to live on the MP surface, modifying their structural properties such as molecular weight and strength. This changes the MPs' structure to be hydrophilic making it easier to degrade by active sites on the enzymes. Amino acids at the active sites play a crucial role in the MPs degradation. The extracellular secretions released by microorganisms on the surface of MPs lead to degradation of the MP's polymer chains. The MPs are broken down into monomers by a variety of enzymatic processes, including hydroxylation, oxidation, and hydrolysis. Thus, MPs are also remedied by microbial films via metabolic breakdown. Catalytic enzymes produced by biofilms break down polymers and are influenced by the dynamics of the biofilm (Ali et al., 2024) as summarized in **Figure 6**. Microbial biofilms are effective in MP remediation via biochemical degradation. Microbe-associated MPs degradation is influenced by environmental factors like solar radiation, organic matter, and particulate matter. Biofilms on MPs boost enzyme synthesis, which may improve the breakdown of synthetic polymers. Numerous microbes, such as *Alcanivorax borkumensis* and *Ideonella sakaiensis*, play an efficient role in the degradation of plastic. Plastic degradation is intricately linked to biofilm dynamics, which includes changes in microbial communities like *Rhodobacterales*, *Burkholderiales*, and *Oceanospirillales*. Strains of bacteria such as *Bacillus cereus* and *Bacillus gottheilii* have successfully removed a range of MPs from mangrove areas (Arif et al., 2024). However, Shaji, et al. (2025) emphasized the role of environmental circumstances and the physicochemical characteristics of MPs on microplastic bioremediation. Environmental factors that have a major influence on microbial growth and enzymatic activity include pH, temperature, salinity, nutrient levels, and UV radiation. Higher degradation rates are supported by ideal pH and temperature levels, but biofilm development may be impeded by elevated salinity. MP surfaces may change as a result of UV exposure, increasing them vulnerability to microbial degradation. MP properties such surface roughness, hydrophobicity, crystallinity, and particle size influence microbial colonization and degradation. Surfaces that are rougher and less hydrophobic promote the growth of biofilms and microbial adhesion. Microbial degradation is accelerated by smaller particles and lower crystallinity. However, the breakdown efficiency can be decreased by plastic additives such as biocides and anti-fouling chemicals (such as chlorothalonil) that prevent microbial activity and biofilm development.

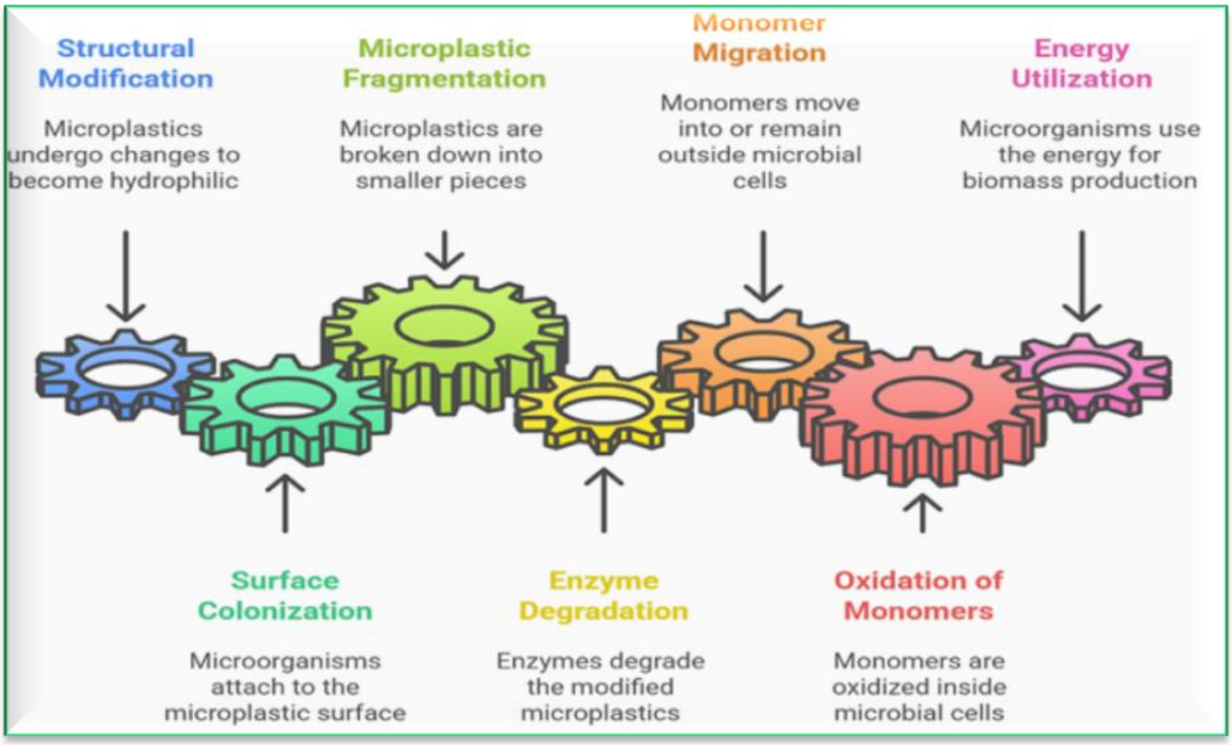

Fig. 6. Bioremediation pathway of microplastic as summarized from (adapted from Ali et al., 2024).

4.3. Biochar utilization in microplastic remediation from soil

Biochar is a carbonaceous-rich biomass produced by pyrolysis in anoxic conditions. Biochar (BC) has many functional groups, a well-developed pore structure, and a large specific surface area. It attracts wide attention due to its unique properties and thus can be utilized in enhancing soil nutrients, improving crop productivity and carbon sequestration, and remediating soil contamination (Su et al., 2024; Wang et al., 2024; Lin et al., 2025; Yu et al., 2025). Due to its unique properties, BC is effective in mitigating MP impacts on plants (Elbasiouny et al., 2023; Yu et al., 2025). Recently, BC has attracted special interest due to its easy availability, stable characteristics, and advantages in resource recycling. Biochar has been confirmed to degrade and immobilize pollutants owing to its remarkable adsorption capacity and redox properties. Research shows BC may positively influence plastic waste degradation and its additional components, potentially due to enhancing microbial activity or its role as an "electron shuttle" in facilitating electron-transfer reactions. Moreover, BC possessing electrochemical properties has participated in various redox reactions in soil and water (Zou et al., 2024).

Thus, BC can play multiple beneficial roles in soil including fostering the degradation of MPs, or as we say “one stone, three birds”, including soil fertility, carbon sequestration, and pollution remediation. These roles include stimulating MP-degrading bacterial activities, facilitating the breakdown and mineralization of intermediate degradation products, and enhancing the soil environment (**Figure 7).** These effects are closely linked to BC physical and chemical properties, such as its redox-active capacity, porous structure, and nutrient bioavailability (Zou et al., 2024). After MPs and BC are introduced into the soil, their interactions with each other and with the soil can change the soil's capacity to adsorb pollutants. This results in lowered concentrations of contaminants in soil pore water and alterations to several processes, including pollutant transport and bioavailability within the soil environment (Shang et al., 2024). Biochar can retain MP particles through mechanisms such as trapping, sticking, and entangling MP spheres. In addition, BC can actively adsorb MPs by decreasing electrostatic repulsion or creating chemical bonds between its particles and MPs (**Figure 8**) (Li et al., 2024). Chai et al. (2024) added that BC can interact with MPs because it contains many functional groups which include oxygen. As a result, the migration behavior of MPs is restricted and their environmental risk is decreased. Several authors used BC in the remediation of MPs-contaminated soil, as summarized in **Table 3.** However, the effectiveness of using biochar for remediation and alleviation of the adverse effects of MPs is still uncertain (Wu et al., 2024). Although some research focused on BC’s ability to remove MPs from soil and addressed some of the mechanisms mentioned above, the current focus of research on biochar's potential to alleviate the toxicological impacts of MPs on plants is mainly on physiological and biochemical responses, with a lack of exploration into the molecular mechanisms involved (Liu et al., 2025).

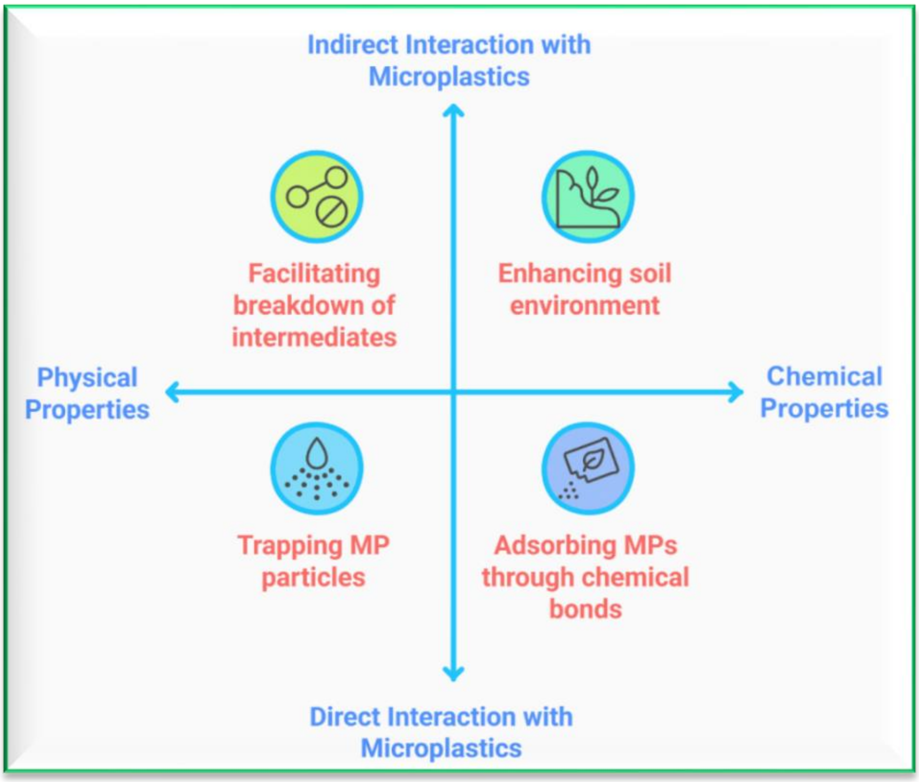

Fig. 7. Biochar's role in microplastic degradation.

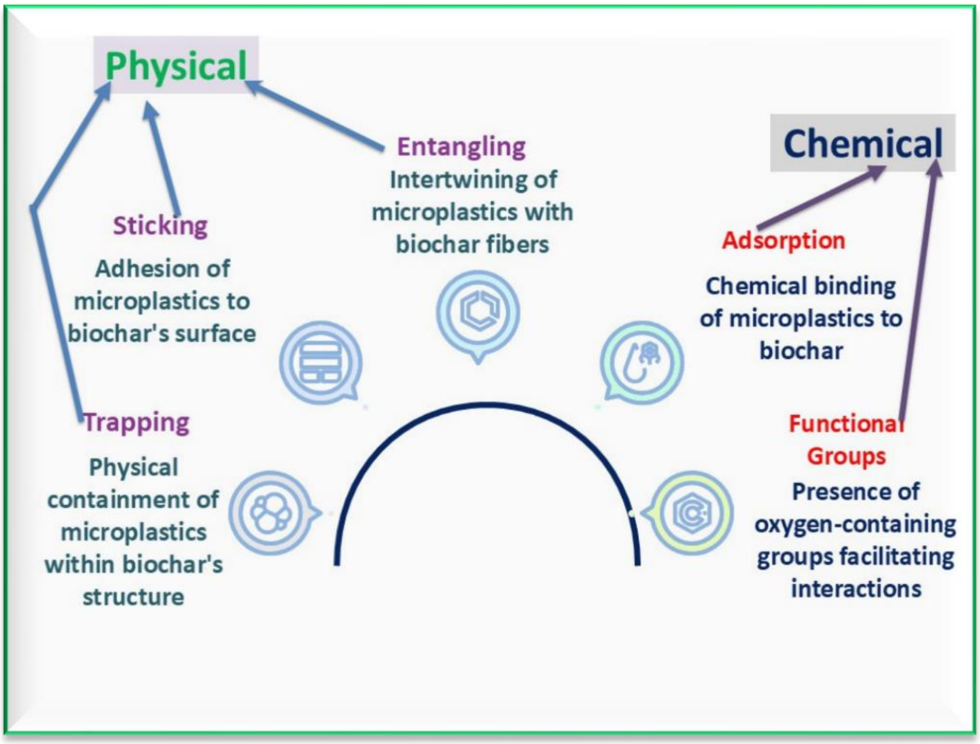

Fig. 8. Biochar's mechanisms of interaction with microplastics.

Table 3. The effectiveness of biochar in removing microplastic particles in soil or mitigating their negative impacts.

Microplastic type (concentration)	Biochar details	Experiment condition	Outcomes	Reference
Polyethylene and polylactic acid (1%)	Rice straw, 1% of soil mass	Incubation of soil to raise tobacco	BC can remediate MP contaminated soil and alleviate their negative effects on the soil.	Wang et al. (2024)
Polyethylene (25 MPs particles)	Coconut shell, 50 mL leached BC, 10 g bulk-BC	Farmland soil contaminated by antibiotics	MPs altered soil properties and increased antibiotic resistance genes, while BC inhibited antibiotic resistance genes.	Su et al. (2024)
Polyethylene and polylactic acid (0.5%)	Modified and unmodified BC from elderberry *(S. canadensis* L.) (1 %)	Pot experiment	Modified BC was superior to unmodified BC in mitigating the toxicity of MC inhibited antibiotic resistance genes.	Iqbal et al. (2025)
Polypropylene, blue polyethylene and red polystyrene (20 particles of MP L^{-1})	Corn stalks, 125g / 2500 g of soil	Column experiment	BC removed 90 % of MPs enhanced with vegetated column, with maximum microbial enrichment in the vegetated biochar column.	Ahmed et al. (2025)
Polyethylene and Polylactic acid (0.2 and 2 %)	Rice straw (3%)	Brown soil	The toxic effect of polyethylene is higher than polylactic acid, with a stronger effect with higher concentrations. Adding BC alleviated toxic effect of MPs with varied levels.	Liu et al. (2025)
Rubber crumb (0.5 and 10%)	Corn stalks, 1 g of BC inoculated with 2.5 mL PGPR bacterial solution	Pot experiment	MPs significantly reduced the dry weight of the peanut shoot, root vigor and nodule numbers, plant enzyme activity, soil dehydrogenase and urease activity, soil available K, and bacterial abundance. Applied BC increased the plant biomass, enzymatic antioxidants, soil enzymes, and bacterial diversity .	Yu et al. (2024)
Polyethylene (0.5 and 1 g kg^{-1} of soil)	Aleppo pine branches and trunk (6 and 10 g kg^{-1} of soil)	Pot experiment	Plant chlorophyll decreased, especially with lower MP dose, however, BC and MP enhanced chlorophyll *a,* especially with higher BC dose. Barley grain yield decreased in BC and lower MP dose.	Debab et al. (2024)
Polystyrene (Suspension as 10 mg L^{-1})	Wood (5, 10, and 15%)	Column tests	Without BC, more MPs escaped from samples due to wetting-drying cycles; however, adding 15 % BC significantly reduced MPs escaping into the effluent.	Li et al. (2024)
Polystyrene (1.82×10^8 mL^{-1})	Wheat straw (0.03 g) at different pyrolysis temperatures	Kinetics experiment with clay and sandy soil	MPs removed up to 86% of MPs, with enhanced removal efficiency with higher pyrolysis temperature.	Chai et al. (2024)
Polystyrene (1.5 %)	Peanut shell (2 %)	Pot experiment – brawn sandy loamy clay soil	MPs inhibited plant root growth and the function and diversity of rhizosphere bacteria; BC promoted the key gene expressions associated with lignin synthesis, antioxidant activities, energy metabolism, and nitrogen transport.	Yang et al. (2024)

5. Future research needs

Microplastic contamination in soil is becoming more well-recognized, yet there are still significant information gaps. Priorities for the following research are crucial for managing and cleaning up MP contamination in soils:

1) Future research must concentrate on how soil particles, organic matter, and microbial communities interact in various environmental settings in order to make key predictions about MP mobility, bioavailability, and fate in soil.

2) Standardized techniques are desperately needed to find, identify, and measure MPs in complicated soil matrices, particularly at smaller size ranges (<1 mm), trustworthy,

3) long-term research is necessary o investigate the long-term impacts and environmental risk assessment of MPs and their degradation products on plant health, soil biodiversity, and food safety. Effects on microbial enzymatic activities, crop yield, and soil fertility should all be investigated.

4) Eco-friendly, scalable, and economical remediation methods that do not degrade soil quality are required; these methods should concentrate on integrated approaches including biodegradation, bioelectrochemical methods, and combination phytoremediation-bioremediation tactics.

5) Although plants can absorb MPs, their function is restricted in the absence of degradation that guarantees efficient MP breakdown in the rhizosphere, future studies must investigate methods that integrate phytoremediation with microbial or enzymatic degradation.

6) To control the use of agri-plastics, encourage biodegradable alternatives, and handle plastic waste, stricter regulations are required. Campaigns to raise public awareness should highlight how plastic pollution affects food systems and soil health.

7) Interdisciplinary cooperation amongst agronomists, environmental engineers, microbiologists, soil scientists, and policymakersto to address MP contamination in soils

6. Conclusions

Soil pollution is a very old problem that started with the beginning of humanity. This pollution was increased by industrialization. Soil plastic pollution is considered one of the most significant global issues facing modern society. Plastics have penetrated virtually all aspects our lives. The sources and risks of such pollution in agricultural soils are of great concern all over the world. The potential degradation of soil plastics into microplastics, nanoplastics, and other by-products is a crucial issue facing humanity. It must be solved to protect environmental and human health. Although effective remediation approaches are urgently needed to address the existing soil microplastic problem, avoiding or reducing future accumulation of plastics in the environment would be the ideal approach.

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