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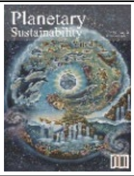

SILENT ACCUMULATION OF MICROPLASTIC POLLUTION IN TERRESTRIAL ECOSYSTEMS

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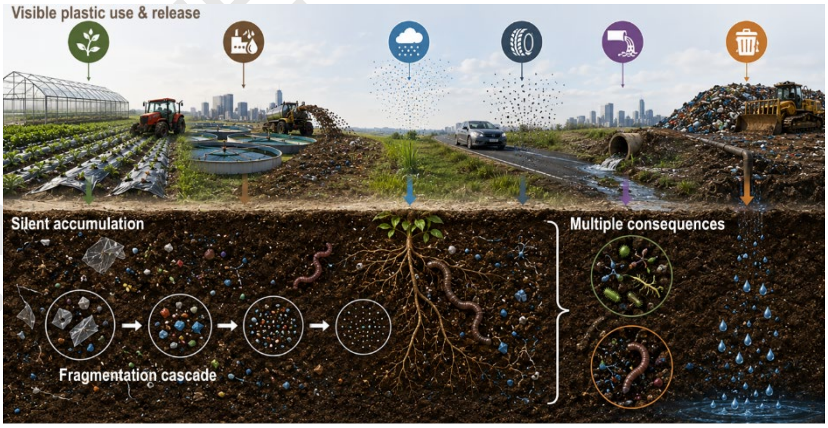
HIGHLIGHTS

- Terrestrial ecosystems are important but underrecognised sinks of microplastic pollution.
- "Silent accumulation" describes the progressive persistence and fragmentation of plastics in soils.
- Future plastic leakage may substantially increase terrestrial microplastic burdens under business-as-usual scenarios.
- MPs threaten soil functions, biodiversity, and ecosystem resilience.
- Prevention, predictive monitoring, and sustainable material innovation are essential for long-term soil protection.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastic (MP) pollution is widely recognised as a global environmental challenge, yet scientific and policy attention has focused predominantly on aquatic ecosystems despite growing evidence that terrestrial environments are major and increasingly recognised, sinks of plastic contamination. Global plastic production has already exceeded 400 Mt annually and is projected to surpass 1,100 Mt by 2060 under business-as-usual scenarios. While an estimated 19 to 23 Mt of plastic waste enters aquatic ecosystems each year, terrestrial inputs are believed to be substantially higher under many current estimates, due to agricultural plastics, sewage sludge

modelling, food security, climate change, sustainable materials

application, atmospheric deposition, urban runoff, and landfill leakage. Consequently, soils are becoming long-term reservoirs of plastic pollution through the process we define here as "silent accumulation", the progressive, often unnoticed build-up, persistence, fragmentation, and continuous generation of secondary micro- and nanoplastics within terrestrial ecosystems. Although existing studies have documented sources, pathways, occurrence, and ecological effects of MPs in soils, this perspective moves beyond a descriptive synthesis by introducing the concept of silent accumulation as a conceptual framework and integrating current evidence with published future scenarios to examine how terrestrial microplastic contamination may evolve under business-as-usual conditions. Current evidence demonstrates that MPs can alter soil structure, microbial communities, soil fauna, nutrient cycling, and plant performance, whereas published OECD and UNEP projections suggest that continued increases in plastic production, waste generation, environmental leakage, and secondary microplastic formation could intensify terrestrial MP accumulation throughout the coming decades. Major uncertainties remain regarding long-term accumulation rates, ecological thresholds, legacy plastic fragmentation, climate-change interactions, and future contamination burdens. We therefore highlight the need for coordinated global monitoring networks, long-term datasets, and predictive models capable of forecasting terrestrial MP trajectories and identifying critical stress thresholds. Advancing terrestrial microplastic research from a largely descriptive field toward a predictive science is essential for informing preventive policies, protecting soil health, and safeguarding the long-term sustainability of terrestrial ecosystems through standardised monitoring, long-term field studies, predictive modelling, source prevention, and rigorous evaluation of sustainable alternative materials.

Introduction

For decades, the global narrative on plastic pollution has been dominated by its visible presence in aquatic environments. Iconic images of floating debris in the Great Pacific Garbage Patch and entangled marine wildlife have galvanised public awareness and policy action (OECD, 2024). Although this attention has substantially advanced understanding of plastic pollution in aquatic systems, growing evidence indicates that terrestrial ecosystems are also major recipients of plastic contamination and deserve greater scientific and policy attention. While an estimated 19 to 23 million metric tons (Mt) of plastic waste enter aquatic environments annually (UNEP, 2025), recent assessments indicate that terrestrial plastic pollution is likely 4 to 23 times higher than aquatic loads (UNDP, 2021). This disparity arises because land acts as one of the principal long-term sinks for mismanaged plastic waste, with soils receiving direct inputs from agricultural practices, landfill leachate, atmospheric deposition, and wastewater sludge application (Büks & Kaupenjohann, 2020; UNDP, 2021).

In this perspective, we define "silent accumulation" as the progressive, often unnoticed build-up, persistence, fragmentation, and continuous generation of plastic particles within terrestrial ecosystems, resulting in increasing contamination over time despite limited visual evidence. The term "silent" reflects the fact that, unlike conspicuous plastic debris in aquatic environments, terrestrial microplastic accumulation generally proceeds without obvious visual indicators, allowing contamination to intensify gradually while remaining largely undetected until ecological consequences begin to emerge. Unlike marine plastics, which are often visible on coastlines or surface waters, microplastics (MPs, defined as particles ≤ 5 mm) in soil are hidden within the complex pedosphere matrix, making them difficult to detect, quantify, and visualise (Büks & Kaupenjohann, 2020). This invisibility has led to a significant regulatory and research lag; while marine MP monitoring protocols have received greater methodological attention and is progressing toward harmonisation, terrestrial systems still lack widely accepted protocols for extraction and identification, resulting in fragmented data and an underestimation of the true ecological burden (Campanale *et al.*, 2024). As a result, soils are becoming long-term reservoirs of legacy plastics, accumulating fragments that will persist and fragment further for centuries, creating a "plastic smog" that is extremely difficult to remediate at field scale once established (UNDP, 2021).

The root of this accumulation lies in the exponential growth of global plastic production, which has surpassed 400 Mt annually since the early 2020s, driven by the increasing demand for plastic materials across packaging, consumer products, construction, transportation, and agricultural applications (Plastics Europe, 2022; UNEP, 2025). Despite decades of recycling initiatives, the global circularity rate for plastics remains critically low, with only approximately 9% of plastic waste being recycled (OECD, 2022a). The majority ends up in landfills, incinerators, or leaks directly into the environment. Packaging remains the largest single market segment, accounting for 39.9% of total global plastic production, and its short service life combined with high leakage rates makes it a major contributor to environmental plastic pollution (Plastics Europe, 2022; UNEP, 2025).

Agricultural systems represent one of the most important pathways through which plastics directly enter terrestrial ecosystems. Approximately 4% of global plastic production is consumed directly by the agricultural sector, primarily in the form of mulching films, greenhouse covers, irrigation pipes, and silage wraps (UNDP, 2021; Campanale *et al.*, 2024). These applications involve direct contact with soil, meaning that any fragmentation or incomplete removal results in immediate contamination of the arable layer. The use of conventional polyethylene (PE) mulch films is widespread due to their ability to suppress weeds, conserve moisture, and increase crop yields (Campanale *et al.*, 2024). However, these films are rarely fully recovered after harvest; residual fragments are tilled into the soil, where they undergo photodegradation and mechanical fragmentation, transforming into secondary MPs that integrate into the soil structure (UNDP, 2021).

Recent meta-analyses and field studies have begun to quantify this hidden burden. A comprehensive review by Büks and Kaupenjohann (2020) reported average MP concentrations of approximately 1.7 mg kg^{-1} in agricultural soils globally, with significant variability depending on farming practices and soil type. These particles are increasingly recognised as biologically and physically active components of soil systems rather than inert contaminants. Once accumulated in soil, they can interact with soil structure, influence water dynamics, alter microbial communities, and affect key ecosystem functions, thereby contributing to long-term ecological change (Campanale *et al.*, 2024).

Furthermore, the morphology of soil MPs differs from aquatic MPs. While fibres and fragments are common in both, agricultural soils particularly those under plastic mulching are often enriched with film fragments and fibres derived from synthetic textiles in sewage sludge. The frequent detection of PE, Polypropylene (PP), together with Polyethylene Terephthalate (PET), Polyamide (PA/Nylon), Polyvinyl Chloride (PVC), or Polystyrene (PS) depending on source pathway reflects the materials most commonly used in packaging, consumer products, and agricultural applications (Büks & Kaupenjohann, 2020; Plastics Europe, 2022; Campanale *et al.*, 2024). These polymers are resistant to biological degradation under ambient soil conditions, leading to cumulative persistence that outpaces natural attenuation processes.

Despite the growing number of reviews describing terrestrial microplastic occurrence and ecological effects, comparatively little attention has been devoted to conceptualising how plastic contamination progressively accumulates in soils over time or to integrating current evidence with published future projections. Rather than providing another descriptive review, this perspective introduces the concept of “silent accumulation” as a conceptual framework for understanding the long-term build-up of terrestrial microplastics and examines how ongoing plastic production, environmental leakage, and fragmentation may shape future contamination trajectories under business-as-usual scenarios.

This perspective article aims to synthesise the current state of knowledge on MP pollution in terrestrial ecosystems, with a specific focus on agricultural soils as a critical hotspot. We critically assess the sources, pathways, and current burdens of soil MPs, drawing on recent meta-analyses and field data. Crucially, we examine the likely future trajectory of this pollution under business-as-usual scenarios, drawing upon published OECD and UNEP scenarios rather than original predictive modelling. Finally, we identify the key scientific and policy challenges that must be addressed to mitigate this silent crisis, arguing for a paradigm shift from end-of-pipe remediation to preventive material substitution and standardised global monitoring. By illuminating the scale and urgency of terrestrial MP accumulation, this work seeks to catalyse targeted research and policy actions to protect soil health and planetary sustainability. Figure 1 presents a conceptual framework illustrating the sources, transformation processes, environmental fate, ecological impacts, and prevention pathways associated with the silent accumulation of MPs in terrestrial ecosystems.

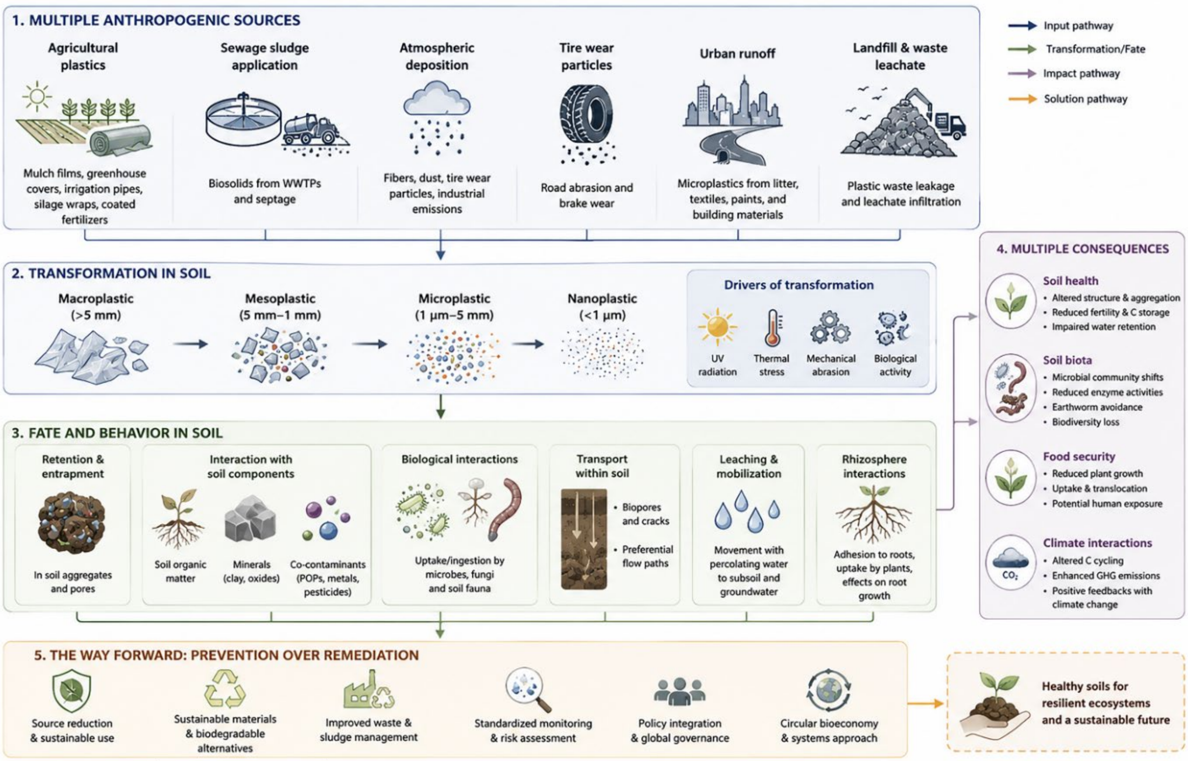

Figure 1: Conceptual framework of microplastic inputs, transformation pathways, and environmental consequences in terrestrial ecosystems

Sources And Pathways: How Plastics Enter the Soil

The accumulation of MPs in terrestrial ecosystems is driven by multiple interconnected anthropogenic pathways that differ substantially in their magnitude, spatial distribution, evidence strength, and potential for mitigation (Figure 1). Unlike aquatic systems, where hydrodynamic forces distribute pollutants, soils act as a primary sink, retaining MPs due to their physical entrapment in soil aggregates and adsorption to organic matter (Rillig *et al.*, 2019). These inputs introduce distinct polymer types, morphologies, and chemical additives, creating a heterogeneous contamination landscape across terrestrial environments (de Souza Machado *et al.*, 2018; Hurley & Nizzetto, 2018).

Agricultural Practices: The Direct Input Hotspot

Agricultural activities represent one of the most important and best-documented pathways for MP entry into terrestrial ecosystems, primarily through the use of plastic-based materials that are directly applied to or used in contact with soils. Globally, the agricultural sector consumes approximately 4% of total plastic production, primarily in the form of mulching films, greenhouse covers, irrigation pipes, and silage wraps (UNDP, 2021). Plastic mulching, particularly the use of Low-Density Polyethylene (LDPE), is widely adopted to enhance crop yield by regulating soil temperature, conserving moisture, and suppressing weeds (Steinmetz *et al.*, 2016). However, the recovery of these thin films is often incomplete. Mechanical harvesting and tillage cause films to fragment, leaving substantial residues in the soil. Studies estimate that in intensive agricultural regions such as parts of China and Europe, residual plastic film accumulation can reach 100 to 400 kg per hectare, contributing substantially to long-term soil plastic contamination (E K Liu *et al.*, 2014; Qi *et al.*, 2020; Cusworth *et al.*, 2022; Campanale *et al.*, 2024; Zhou *et al.*, 2025).

Once in the soil, these macro- and mesoplastics undergo abiotic degradation via UV radiation (if surface-exposed), thermal stress, and mechanical abrasion from tillage, fragmenting into secondary MPs (Andrady, 2011). These fragments persist for decades to centuries due to the low microbial activity against synthetic polymers in ambient soil conditions. Beyond mulching, other agricultural inputs contribute to the burden. Drip irrigation tapes, often made of PE, degrade over time, releasing fragments into the root zone. Additionally, the use of polymer-coated controlled-release fertilisers introduces synthetic shells directly into the soil matrix, which may fragment before complete nutrient release.

Waste Management and Land Application: The Sewage Sludge Vector

Wastewater Treatment Plants (WWTPs) are effective at capturing MPs from urban wastewater, removing up to 90% to 99% of incoming particles through sedimentation and filtration processes (Murphy *et al.*, 2016). However, this efficiency comes at a cost: The captured MPs concentrate in the resulting sewage sludge (biosolids). In many countries, including members of the European Union and the United States, sewage sludge is applied to agricultural land as a fertiliser or soil conditioner due to its high nutrient content (Nizzetto *et al.*, 2016). This practice transfers significant MP loads from urban centres to rural soils. Although this pathway is well documented, its contribution varies considerably among countries because biosolid application practices differ substantially according to regional regulations and agricultural management systems.

Recent estimates suggest that annual MP inputs from sludge application can range from 0.01 to 0.5 tons per hectare, depending on sludge quality and application rates (Mahon *et al.*, 2016). The MP composition in sludge is diverse, reflecting urban sources. Common detected polymers are Polyethylene Terephthalate (PET) fibres from synthetic textiles, Polyethylene (PE) fragments from packaging, and Polyamide (PA) fibres. Unlike agricultural mulch, which is predominantly PE, sludge-derived MPs introduce a wider variety of polymers, reflecting the diverse plastic sources present in municipal wastewater streams. Long-term application of sludge has been linked to increased MP concentrations in topsoil layers (Huang *et al.*, 2026). For example, agricultural soils receiving sludge-derived amendments at approximately 30 $t.ha^{-1}.yr^{-1}$ for 2 years and 15 $t.ha^{-1}.yr^{-1}$ for five years contained 545.9 and 87.6 MP items kg^{-1} soil, respectively, compared with only 5.0 items kg^{-1} in non-amended soils (Zhang *et al.*, 2020), while concentrations of up to 3,500 particles kg^{-1} have been reported following 10 years of sewage sludge application (Corradini *et al.*, 2019).

Atmospheric Deposition: The Invisible Rain of Plastics

Atmospheric deposition has emerged as a critical, yet often underestimated, pathway for MP contamination in terrestrial ecosystems. Airborne MPs originate from various sources, including tyre-wear particles (TWPs) from road traffic, abrasion of synthetic textiles, industrial emissions, and wind erosion of plastic- laden soils. These particles can remain suspended in the atmosphere for extended periods and travel long distances before settling via dry or wet deposition (Brahney *et al.*, 2020).

Recent studies have detected MPs in remote areas, including mountain peaks and protected natural reserves, confirming the global scale of atmospheric transport (Bergmann *et al.*, 2019; Habibi *et al.*, 2022). In agricultural contexts, atmospheric deposition adds a background load of MPs to water and soils, independent of local farming practices. Tyre wear particles, composed of Styrene-Butadiene Rubber (SBR) and various additives (e.g., zinc, 6PPD) are estimated to be one of the largest sources of MP pollution globally, with significant deposition in freshwater and roadside soils (Tian *et al.*, 2021). The morphology of airborne MPs is predominantly fibres and irregular fragments, which can accumulate on plant surfaces and eventually enter the soil through leaf litter decomposition or rainwash (Wright *et al.*, 2020).

Urban Runoff and Landfill Leachate

Compared with agricultural inputs, however, contamination from urban runoff is generally more localised and strongly influenced by surrounding land use and stormwater management practices. Stormwater carries litter, tyre particles, and road dust into green spaces, gardens, and peri-urban agricultural lands (Ziajahromi *et al.*, 2016). The intensity of this input correlates with urbanisation levels and precipitation events, leading to localised hotspots of contamination (Wang *et al.*, 2022). Similarly, landfills represent a long-term source of MPs. As plastic waste degrades in landfills, it releases leachate containing MPs and associated chemical additives (e.g., phthalates, bisphenol A) into the surrounding soil and groundwater (Sekar *et al.*, 2026). While modern landfills are engineered to minimise leakage, older or unregulated sites pose significant risks of soil and aquifer contamination.

In addition, organic amendments such as composts (Weithmann *et al.*, 2018; Porterfield *et al.*, 2023), digestates (Porterfield *et al.*, 2023; Alimohammadi & Demirer, 2024), manure-derived fertilisers (Tang *et al.*, 2025), and sludge-based products (Corradini *et al.*, 2019; Zhang *et al.*, 2020) have emerged as important but often overlooked pathways for MP introduction into terrestrial ecosystems. These materials can contain substantial quantities of plastic fragments and fibres originating from household waste, packaging residues, wastewater treatment processes, agricultural activities, and other contaminated waste streams. Their repeated application to agricultural soils may result in the gradual accumulation of MPs over time, thereby contributing to diffuse and persistent soil contamination across large agricultural areas.

Collectively, current evidence indicates that agricultural plastic mulching and sewage sludge application represent the best-documented and most direct sources of microplastics in agricultural soils, supported by numerous field investigations and long-term observations. Atmospheric deposition and tyre wear particles are increasingly recognised as important contributors, although their relative importance varies considerably among regions and remains more difficult to quantify because of long-range transport and multiple emission sources. Urban runoff and landfill leakage generally contribute more localised contamination but may become significant in densely populated or poorly managed waste-disposal areas. From a management perspective, agricultural plastics and sludge applications are among the most readily preventable pathways through improved material design, recovery practices, and waste-management strategies, whereas atmospheric deposition and tyrewear require broader technological innovations and policy interventions extending beyond the agricultural sector.

Current Status: Quantifying the Burden

Despite the growing recognition of terrestrial MP pollution as a critical environmental issue, quantifying the exact burden in soils remains a significant scientific challenge. Unlike aquatic systems, where water column sampling is relatively standardised, soil matrices are heterogeneous, complex, and rich in organic matter, which interferes with MP extraction and identification (Hurley & Nizzetto, 2018). Consequently, reported concentrations vary widely across studies, influenced by land use, soil type, depth, and analytical methods. Although recent meta-analyses and field surveys have substantially improved our understanding of current contamination levels, important uncertainties remain because of geographic data gaps and methodological inconsistencies among studies.

Occurrence, Distribution, and Accumulation of Microplastic in Agricultural Soils

MP concentrations in agricultural soils average approximately 1.7 mg kg^{-1} (dry weight) (Büks & Kaupenjohann, 2020). In regions with intensive plastic mulching such as parts of China, Europe, and North America, concentrations can be substantially higher. For instance, studies in Chinese agricultural fields using long-term plastic mulching have reported MP abundances ranging from 0.85 to 67.12 mg kg^{-1} soil, averaging 9.96 mg kg^{-1} in the topsoil layer (Yu *et al.*, 2023). In European contexts, where sewage sludge application is common, MP concentrations in arable soils have been estimated at 0.01 to 0.5 tons per hectare annually due to biosolids amendment, leading to cumulative loads that may reach several hundred mg kg^{-1} over decades (Mahon *et al.*, 2016; Nizzetto *et al.*, 2016).

The vertical distribution of MPs in soil represents another important source of uncertainty. To date, most studies have focused on the topsoil (0 to 20 cm), where inputs are highest and biological activity is most intense. However, earthworms and other soil fauna can transport MPs to deeper layers (up to 50 cm or more), potentially affecting subsoil ecosystems and groundwater quality (Rillig *et al.*, 2017; Zhang *et al.*, 2025). A study by Zhang *et al.* (2025) demonstrated that earthworms (*Lumbricus terrestris*) can facilitate the vertical migration of MPs, creating macropores that serve as conduits for particle transport (Zhang *et al.*, 2025). This bioturbation process complicates the assessment of total soil MP burdens, as surface sampling may underestimate the total reservoir stored in the pedosphere.

Collectively, these observations provide strong evidence that MPs are already widespread in agricultural soils, although the magnitude of contamination remains highly variable among regions because of differences in agricultural practices, plastic use, and analytical methodologies.

Types and Morphologies of Soil MPs

The polymer composition and morphology of soil MPs reflect their diverse sources. PE is consistently identified as the most abundant polymer in agricultural soils, often accounting for approximately 30% to 70% of detected MPs depending on local agricultural practices and plastic use intensity, primarily due to the fragmentation of mulch films and irrigation pipes (Steinmetz *et al.*, 2016; Büks & Kaupenjohann, 2020). PP is frequently the second most abundant polymer, typically representing 10% to 30% of detected particles, while PS, PET, and PVC generally occur at lower but variable proportions depending on land use and waste management practices (Büks & Kaupenjohann, 2020; Campanale *et al.*, 2024). In sludge-amended soils, the polymer spectrum becomes more diverse, with PET fibres and PA (nylon) commonly reported due to inputs from synthetic textiles and municipal wastewater streams (Nizzetto *et al.*, 2016). This distinction is crucial because different polymers have varying degradation rates, toxicities, and interactions with soil biota.

Morphologically, soil MPs are dominated by fragments, films, fibres, and pellets, although their relative abundance varies considerably among agricultural systems. For example, a study of agricultural soils in northern China reported fragments as the dominant morphology (37.7%), followed by films (33.9%), fibres (21.9% to 29.6%), and pellets (4.2% to 6.6%) (Zhang *et al.*, 2021). Fragments are frequently associated with the weathering and mechanical breakdown of larger plastic items such as mulch films and agricultural infrastructure, whereas fibres are commonly linked to atmospheric deposition and the application of sewage sludge or other organic amendments (Büks & Kaupenjohann, 2020). However, fibre abundance may be underestimated in many studies because fibres are analytically challenging to identify and are often subject to stricter contamination-control procedures during sample processing (Dris *et al.*, 2015). Films, foams, and pellets generally occur at lower abundances, although their prevalence depends strongly on local plastic-use practices and source pathways.

Table 1: Critical knowledge gaps, evidence strength, and research priorities for terrestrial microplastic pollution

Theme	Current Understanding	Key Uncertainty	Evidence Strength*	Priority Action	Key References
Soil occurrence and burden	MPs are widely detected in agricultural and urban soils, but concentrations vary strongly by land use, depth, and analytical method	True global soil burden remains uncertain due to fragmented sampling and reporting	Moderate–high	Establish harmonised global monitoring networks using comparable units and size classes	Horton *et al.* (2017), Büks and Kaupenjohann (2020), Boctor *et al.* (2025)
Source attribution	Major inputs include agricultural plastics, sewage sludge, atmospheric deposition, tyre wear, urban runoff, and landfill leakage	Relative contribution of each pathway remains poorly quantified at regional and global scales	Moderate	Develop source-apportionment approaches combining polymer fingerprints, additives, and land-use data	Nizzetto *et al.* (2016), Brahney *et al.* (2020), Wang *et al.* (2022), Sekar *et al.* (2026)
Analytical standardisation	Density separation, µ-FTIR, Raman spectroscopy, and Py-GC/MS are widely used	Different extraction methods, size cut-offs, and reporting metrics limit cross-study comparison	High	Standardise extraction, identification, quality control, and reporting protocols for soils	Hurley and Nizzetto (2018), Sharma *et al.* (2021), Adhikari *et al.* (2022), Huang *et al.* (2022)
Nanoplastics	NPs are expected to be more mobile and bioavailable than larger MPs	Detection and quantification in complex soil matrices remain technically limited	Low–moderate	Advance high-resolution analytical tools for nano-scale plastics in soils and plant tissues	Azeem *et al.* (2021), Adhikari *et al.* (2022), Vleeming *et al.* (2026)
Soil physical and chemical effects	MPs can alter bulk density, porosity, aggregation, water retention, and contaminant transport	Effects vary by polymer type, size, shape, dose, and soil texture	Moderate	Conduct long-term, environmentally relevant field experiments across contrasting soil types	de Souza Machado *et al.* (2019), Rillig *et al.* (2019), Dewi *et al.* (2024), Han *et al.* (2024)
Soil biota and microbiome	MPs influence microbial communities, earthworms, soil fauna, and plastisphere formation	Functional consequences for nutrient cycling, decomposition, and biodiversity remain uncertain	Moderate	Integrate metagenomics, enzyme assays, soil fauna tests, and ecosystem-function measurements	Guo *et al.* (2023), Han *et al.* (2024), Wang *et al.* (2024), Zhang *et al.* (2025)

Plant uptake and food safety	Small MPs and NPs may enter plants through root or foliar pathways and translocate to edible tissues	Field relevance, exposure levels, and human dietary risk remain unresolved	Low–moderate	Prioritise realistic exposure studies in food crops under field and semi-field conditions	Azeem *et al.* (2021), Lazăr *et al.* (2024), Boctor *et al.* (2025), Vleeming *et al.* (2026)
Climate and carbon cycling	MPs may alter soil carbon dynamics, microbial decomposition, and greenhouse gas fluxes	Direction and magnitude of climate feedback remain poorly constrained	Low–moderate	Include MPs in soil carbon and greenhouse gas studies under climate-change scenarios	Rillig *et al.* (2019), Liu *et al.* (2024), Fonseca and Gaylarde (2025)
Future projections and thresholds	Plastic production and environmental leakage are projected to increase under BAU scenarios	Soil-specific accumulation models and ecological thresholds are lacking	Low	Develop predictive soil MP models linked to plastic use, leakage, degradation, and land management	OECD (2022b), Ramanayaka *et al.* (2024), Thompson *et al.* (2024)
Prevention and material substitution	Remediation is impractical at field scale; prevention is more realistic	Many biodegradable plastics do not fully mineralise under ambient soil conditions	Moderate	Evaluate alternatives using soil-biodegradability tests, life-cycle assessment, and field validation	Huo *et al.* (2023), Campanale *et al.* (2024), OECD (2024)

Note: *Evidence strength is assigned qualitatively based on the consistency of available field studies, laboratory experiments, reviews, and global assessments. “High” indicates broad agreement across multiple studies; “moderate” indicates growing but context-dependent evidence; and “low” indicates emerging evidence with substantial methodological or ecological uncertainty

The "Data Gap" and Global Monitoring Needs

Current data on soil MP pollution is heavily biased towards Europe and East Asia, with significant gaps in Africa, South America, the Middle East, and large parts of Central and Southeast Asia (Horton *et al.*, 2017; Büks & Kaupenjohann, 2020). These geographic disparities reduce confidence in current global contamination estimates because rapidly developing regions often differ substantially in agricultural intensification, plastic use, waste-management infrastructure, climatic conditions, and environmental regulations. Consequently, existing global assessments may not fully capture the diversity of terrestrial MP sources, accumulation patterns, or future contamination trajectories. Furthermore, most available studies are cross-sectional, providing only a snapshot of contamination at a single time point, rather than longitudinal datasets required to quantify accumulation rates, persistence, and long-term ecological consequences (Rillig *et al.*, 2019).

As a result, current estimates of terrestrial MP burdens remain associated with considerable uncertainty, particularly in regions where agricultural intensification, urbanisation, and waste-management practices are rapidly changing. Addressing these limitations will require the establishment of coordinated global monitoring networks capable of generating harmonised long-term datasets across diverse climatic zones, soil types, and land-use systems. Such efforts would not only improve estimates of current contamination but also enable the development and validation of predictive models needed to assess future accumulation trajectories and support evidence-based policy interventions. The current understanding of microplastic occurrence, distribution patterns, evidence strength, and key knowledge gaps in terrestrial ecosystems is summarised in Table 1.

Overall, current evidence demonstrates that microplastic contamination is already widespread across many terrestrial ecosystems, particularly agricultural soils. However, considerable uncertainties remain regarding the true global burden because of methodological inconsistencies, uneven geographic coverage, and the scarcity of long-term monitoring datasets. These limitations should be considered when interpreting current estimates and projecting future accumulation trends.

Ecological and Human Health Implications

The accumulation of MPs in terrestrial ecosystems is not merely a physical contamination issue; it represents a multifaceted environmental stressor capable of influencing the pedosphere's chemical, physical, and biological integrity. As MPs persist and fragment, they interact with soil components at multiple scales, influencing processes ranging from soil structure and water dynamics to microbial community composition and ecosystem functioning. The ecological consequences are multifaceted, affecting soil structure, biota health, plant physiology, and potentially human health through trophic transfer.

Impact on Soil Physical and Chemical Properties

MP's act as foreign bodies within the soil matrix, altering its physical architecture and hydrological behaviour. However, the magnitude and even the direction of these effects depend strongly on polymer type, particle size, morphology, concentration, soil texture, and environmental conditions. Studies have demonstrated that MP addition can significantly change soil bulk density, porosity, and aggregate stability (de Souza Machado *et al.*, 2019). For instance, low-density Polyethylene (PE) fragments can increase soil porosity and water-holding capacity in sandy soils by creating voids, whereas high-density polymers like Polyvinyl Chloride (PVC) may compact the soil, reducing infiltration rates (Rillig *et al.*, 2019). These changes are highly dependent on MP morphology. Fibres tend to entangle with soil particles, enhancing aggregate stability but potentially restricting root penetration, while films and fragments can create hydrophobic barriers that reduce soil wettability and disrupt capillary action (He *et al.*, 2023; Dewi *et al.*, 2024).

Effects on Soil Biota and Microbial Communities

Beyond their physical effects on soil structure, MPs can also act as vectors for chemical contaminants. Due to their high surface-area-to-volume ratio and hydrophobic nature, MPs readily adsorb Persistent Organic Pollutants (POPs), heavy metals, and pesticides from the surrounding environment (Bakir *et al.*, 2014). This "vector effect" can increase the exposure of soil organisms to co-contaminants and contribute to localised zones of elevated chemical stress. Furthermore, many plastics contain additives such as phthalates, Bisphenol A (BPA), and flame retardants, which can leach into the soil over time (Lithner *et al.*, 2011). These compounds have been associated with adverse biological effects, including endocrine disruption and toxicity in terrestrial organisms, potentially affecting soil ecosystem functioning and food-web interactions (Wee and Aris, 2017).

Soil microorganisms are fundamental regulators of terrestrial ecosystem functioning, playing essential roles in nutrient cycling, organic matter decomposition, carbon sequestration, soil aggregation, plant health, and food-web interactions. Emerging evidence suggests that MPs can disrupt microbial community structure and function. Meta-analyses indicate that MP exposure can alter bacterial and fungal diversity, often reducing the abundance of key functional groups involved in nitrogen and carbon cycling (Wang *et al.*, 2024). For example, studies have reported shifts in the relative abundance of *Proteobacteria* and *Actinobacteria*, which are critical for organic matter decomposition and nutrient mineralisation (Han *et al.*, 2024). These shifts may be, at least in part, driven by the formation of a "plastisphere", a distinct microbial biofilm that colonises MP surfaces, differing significantly in composition from the surrounding bulk soil microbiome (Yaghoubi Khanghahi *et al.*, 2026). Emerging evidence suggests that the plastisphere may harbour opportunistic pathogens and antibiotic-resistance genes, although the ecological significance of these findings under field conditions remains incompletely understood. (D. Zhang *et al.*, 2025).

For soil fauna, the impacts are more direct and often detrimental. Earthworms, considered ecosystem engineers, are particularly vulnerable. Ingestion of MPs by earthworms (*Lumbricus terrestris*, *Eisenia fetida*) has been shown to cause physical damage to the digestive tract, reduced growth rates, and increased mortality (Guo *et al.*, 2023). MPs can also induce oxidative stress and inflammatory responses in earthworm tissues, compromising their immune function (Jeong *et al.*, 2024). Crucially, earthworms facilitate the vertical transport of MPs into deeper soil layers through bioturbation, potentially exposing subsoil communities to contamination (Schefer *et al.*, 2025). Other soil invertebrates such as collembola (springtails) and nematodes have also been reported to exhibit altered growth, reproduction, behaviour, and survival following MP exposure (Han *et al.*, 2024). These disruptions to the soil food web can have cascading effects on ecosystem services, including decomposition rates and soil fertility.

Plant Uptake and Food Safety Concerns

Interaction between MPs and factories is a critical area of concern for food security. While large MP particles are generally excluded by root systems, recent studies suggest that NPs (<100 nm) and small MPs can be taken up by plants through root cracks, lateral root emergence points, or via endocytosis (Azeem *et al.*, 2021). Once internalised, these particles can translocate to above-ground tissues, including stems, leaves, and fruits (Lazăr *et al.*, 2024). For example, NPs have been detected in the edible tissues of lettuce, wheat, and carrots grown in contaminated soils (Vleeming *et al.*, 2026). MPs and NPs may enter plant tissues through multiple pathways, including root uptake, endocytosis, apoplastic transport, and foliar absorption. Once internalised, these particles can be translocated within plant tissues through transpiration-driven transport processes and may subsequently influence nutrient acquisition, photosynthetic activity, oxidative stress responses, and plant growth. The principal uptake mechanisms and associated biological effects reported in the literature are summarised in Figure 2.

Although evidence for plant uptake has increased considerably in recent years, the efficiency of internalisation, translocation, and accumulation remains highly dependent on particle characteristics, plant species, growth conditions, and experimental design. Furthermore, substantial uncertainties remain regarding the relevance of laboratory observations to field conditions and the long-term implications for crop productivity and food safety.

The presence of MPs in agricultural soils has been associated with phytotoxic effects, including inhibited seed germination, reduced root elongation, and altered photosynthetic efficiency (Shi *et al.*, 2022). However, the underlying mechanisms remain incompletely understood and may involve not only the uptake of plastic particles by plant tissues, but also indirect effects mediated through changes in soil physicochemical properties, nutrient availability, rhizosphere microbial communities, and plant–microbe interactions. Several studies have suggested that oxidative stress, resulting from increased production of Reactive Oxygen Species (ROS), may contribute to cellular damage and impaired plant performance. In addition, MPs may influence nutrient acquisition by modifying soil structure, root-soil interactions, or rhizosphere processes, although the relative importance of these pathways remains unclear and likely varies among plant species, soil conditions, and MP (de Souza Machado *et al.*, 2018; Shi *et al.*, 2022). Although current evidence indicates that MPs and particularly NPs may interact with plants under certain conditions, the extent to which these processes occur under realistic agricultural field conditions, and their implications for human dietary exposure, remain uncertain. Accordingly, precautionary approaches, long-term field investigations, and standardised exposure assessments are needed before robust conclusions regarding food-safety risks can be drawn.

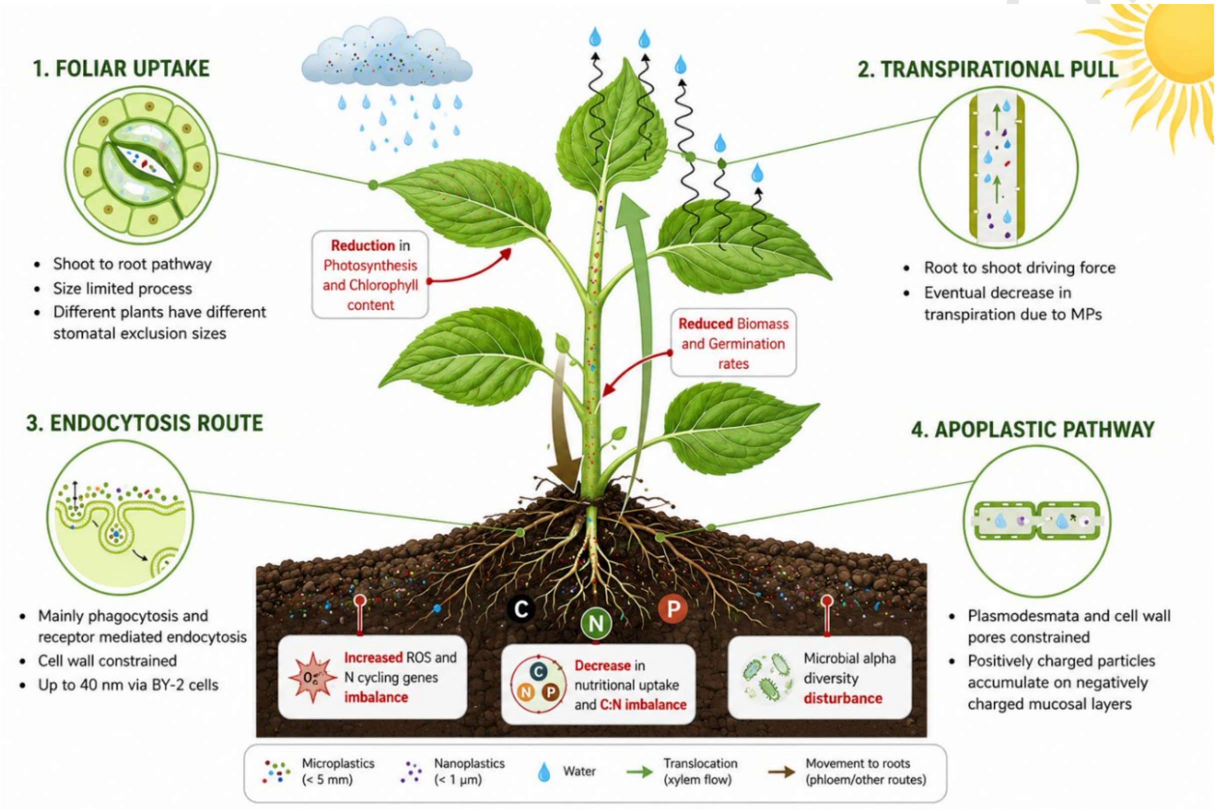

Figure 2: Major pathways of microplastic and nanoplastic uptake, transport, and biological impacts in terrestrial plants. Microplastics and nanoplastics may enter plant tissues through foliar uptake, endocytosis-mediated internalisation, apoplastic transport, and root uptake followed by transpiration-driven translocation. Following internalisation, these plastic particles may influence nutrient uptake, photosynthetic performance, biomass production, oxidative stress responses, microbial interactions within the rhizosphere, and soil nutrient cycling.

Source: Redrawn and adapted from Boctor *et al.* (2025)

Trophic Transfer and Broader Ecological Risks

Beyond direct plant uptake, MPs can move through terrestrial food webs via trophic transfer. Soil fauna that ingests MPs such as earthworms and collembola, are prey for higher trophic levels, including birds, small mammals, and amphibians (Jeong *et al.*, 2024). Studies have documented MP transfer from earthworms to birds, where particles accumulate in the gastrointestinal tract, potentially causing physical blockage and reduced nutrient absorption (Jeong *et al.*, 2024). This potential for trophic transfer and bioaccumulation raises concerns about the broader ecological impacts of terrestrial MP pollution, extending beyond the soil to affect wildlife populations and ecosystem stability (Rochman *et al.*, 2013).

Furthermore, the long-term accumulation of MPs may alter soil carbon sequestration capabilities. By disrupting microbial decomposition processes and altering soil structure, MPs could influence the rate at which organic carbon is stored or released as CO_2 (Liu *et al.*, 2024). Given the critical role of soils in global carbon cycling, any disruption to this function has implications for climate change mitigation efforts. These interactions illustrate that terrestrial MP pollution has implications extending beyond soil ecosystems, reinforcing the need for integrated assessments that consider biodiversity, food production, and climate regulation simultaneously.

The available evidence indicates that microplastics can influence multiple components of terrestrial ecosystems, including soil physical properties, microbial communities, soil fauna, and plant performance. However, the strength of evidence varies substantially among these endpoints. While many ecological effects have been consistently observed under laboratory and controlled experimental conditions, important uncertainties remain regarding long-term field responses, ecological thresholds, and implications for human health. Addressing these knowledge gaps will require coordinated long-term field studies using environmentally realistic exposure scenarios and standardised experimental methodologies.

Future Projections: The Trajectory to 2060

The current accumulation of MPs in soils is not a static phenomenon, but a dynamic process driven by continued plastic production, persistent environmental leakage, insufficient waste-management infrastructure, and the long residence time of synthetic polymers in terrestrial environments. Without significant intervention, the trajectory of soil contamination points toward a substantial increase in MP loads by mid-century, with profound implications for soil health, agricultural productivity, and ecosystem services. This makes future projection a central challenge for terrestrial MP research, requiring integration of plastic production trends, leakage pathways, land-use practices, polymer persistence, fragmentation dynamics, and climate-related stressors.

Published global assessments and modelling studies consistently indicate that plastic pollution will intensify substantially over the coming decades in the absence of ambitious intervention measures. Rising plastic production, population growth, increasing consumption, and persistent shortcomings in waste management are expected to drive continued leakage of plastics into the environment. Although different modelling approaches produce varying quantitative estimates, there is broad agreement that environmental plastic leakage will continue to increase under business-as-usual scenarios.

Figure 3 synthesises published OECD business-as-usual projections to illustrate how projected changes in plastic production, waste generation, recycling, environmental leakage, and secondary microplastic formation may collectively influence future terrestrial contamination. Between 2019 and 2060, global plastic use is projected to increase from 460 to 1,231 Mt (+ 168%), while plastic waste generation rises from 353 to 1,014 Mt (+ 187%), indicating that waste generation is expected to outpace consumption growth. Although the quantity of plastics collected for recycling increases more than fivefold (55 to 302 Mt), this improvement remains insufficient to offset the rapid expansion of plastic consumption. Consequently, the amount of mismanaged and littered plastic is projected to nearly double (79 to 153 Mt), while terrestrial leakage increases from 13 to 26 Mt yr^{-1}. Notably, terrestrial leakage remains consistently more than twice aquatic leakage throughout the projection period (2.2-fold in 2019 and 2.2-fold in 2060), reinforcing the growing recognition that soils, rather than oceans, represent the dominant long-term sink for environmental plastics. Furthermore, the projected increase in secondary microplastic leakage from 2.7 to 5.8 Mt yr^{-1} (+ 115%) suggests that future contamination will increasingly be driven by fragmentation of legacy plastic stocks already present in the economy and environment. This transition from primary plastic pollution to secondary microplastic generation is particularly concerning because it implies that even substantial reductions in future plastic leakage may not immediately halt environmental accumulation. Collectively, these projections indicate that without transformative interventions extending beyond recycling alone, terrestrial ecosystems are likely to experience a sustained and potentially accelerating accumulation of microplastics throughout the coming decades.

The convergence of projections from multiple modelling frameworks provides consistent evidence that current management strategies are insufficient to halt the growth of environmental plastic pollution. According to the OECD baseline scenario, plastic leakage to the environment is projected to double by 2060, reaching approximately 44 Mt annually, while plastics accumulated in aquatic systems are expected to more than triple relative to current levels. Similar trends have been reported by other global assessments despite differences in assumptions and modelling methodologies. These projections reinforce concerns that terrestrial ecosystems will continue to receive increasing plastic inputs, further accelerating the silent accumulation of MPs within soils and increasing pressure on critical ecosystem functions.

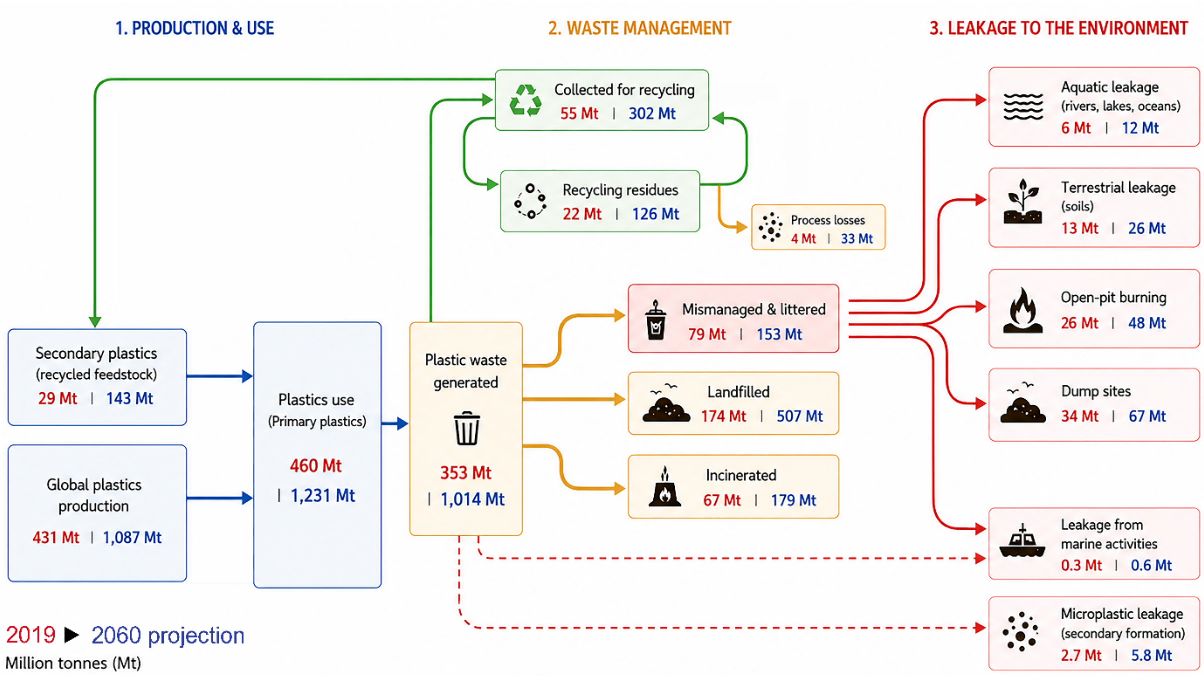

Figure 3: Comparison of global projections of plastic leakage to the environment under business-as-usual scenarios (growth from 2019 to 2060). The figure summarises published OECD business-as-usual scenarios and is intended as a conceptual synthesis rather than an original predictive model. Despite differences in modelling approaches and assumptions, all estimates indicate a continued increase in environmental plastic leakage over the coming decades. The convergence of projections highlights the growing challenge of plastic pollution and the need for coordinated global action to reduce plastic production, improve waste management, and prevent further accumulation of plastics in terrestrial and aquatic ecosystems

Source: Adapted from OECD (2022b)

Business-as-usual (BAU) Scenarios: The Doubling of Production

Under a Business-as-usual (BAU) scenario, global plastic production is projected to more than double by 2060, reaching approximately 1,100 to 1,200 Mt annually (OECD, 2022b; UNEP, 2025). This growth is driven primarily by increasing demand in packaging, construction, and agriculture, particularly in emerging economies where waste management infrastructure often lags behind consumption rates (OECD, 2022b). As shown in Figure 3, environmental plastic leakage is also projected to increase substantially under BAU conditions, with terrestrial leakage rising from 13 to 26 Mt yr^{-1} and secondary microplastic leakage increasing from 2.7 to 5.8 Mt yr^{-1} by 2060.

Independent assessments further suggest that terrestrial ecosystems already receive substantially larger plastic inputs than aquatic systems, with annual terrestrial inputs estimated to be between 3 and 23 times greater than those entering oceans and freshwater environments. Consequently, the cumulative burden of plastics stored in soils may reach gigatonne scales by mid-century if current production and leakage trends persist (Büks & Kaupenjohann, 2020; UNDP, 2021).

Modelling studies suggest that even with improved waste management, the sheer volume of new plastic production will outpace recycling and containment efforts. The OECD's "Global Plastics Outlook" indicates that without drastic policy changes, the amount of plastic leaking into the environment could triple by 2060 (OECD, 2022b). For terrestrial systems, this implies a continuous and accelerating input of MPs from fragmented macroplastics, tyre wear, and agricultural residues. In agricultural hotspots, where plastic mulching is intensifying, soil MP concentrations could increase by an order of magnitude, potentially exceeding thresholds that significantly impair soil function and crop yield (UNDP, 2021; Campanale *et al.*, 2024).

The "Legacy Plastic" Problem and Fragmentation Dynamics

A critical aspect of future projections is the concept of "legacy plastic". Even if global plastic production were halted today, the plastics already present in the environment would continue to fragment and persist for decades to centuries (Campanale *et al.*, 2024). Conventional polymers like PE and PP have half-lives in soil estimated at hundreds of years, meaning that current inputs represent a long-term commitment to contamination (Ramanayaka *et al.*, 2024). As these macroplastics fragment into secondary MPs, the number of particles increases exponentially, even if the total mass remains constant. This progressive fragmentation process, often referred to as a fragmentation cascade, leads to a shift in the size distribution of soil plastics toward smaller, more bioavailable particles (< 1 mm), which pose greater risks to soil biota and plant uptake (de Souza Machado *et al.*, 2018).

Furthermore, the degradation of legacy plastics is not uniform. Environmental factors such as UV radiation, temperature fluctuations, and mechanical stress accelerate fragmentation in surface soils, while deeper layers may preserve larger fragments for longer periods (Ramanayaka *et al.*, 2024). This vertical heterogeneity complicates remediation efforts, as surface cleaning cannot address the reservoir of MPs stored in the subsoil. Consequently, soils are transitioning into permanent sinks for plastic waste, creating a "plastic smog" that is increasingly difficult to manage (UNDP, 2021).

Climate Change Interactions: Feedback Loops and Accelerated Degradation

Climate change is expected to interact synergistically with plastic pollution, potentially accelerating MP generation and altering their ecological impacts. Rising temperatures and increased frequency of extreme weather events such as heavy rainfall and droughts, can enhance the physical fragmentation of plastics in soil (Rillig *et al.*, 2019; Fonseca & Gaylarde, 2025). For instance, intense rainfall can increase runoff, transporting MPs from surface soils into deeper layers or nearby water bodies, while droughts can cause soil cracking, exposing buried plastics to UV radiation and oxidative stress (Rillig *et al.*, 2019).

Moreover, climate change may alter the degradation kinetics of plastics. Higher temperatures can accelerate abiotic degradation processes such as thermo-oxidative breakdown, leading to faster fragmentation rates (Sutkar *et al.*, 2023).

However, this does not imply mineralisation; rather, it speeds up the conversion of macroplastics into MPs and NPs. Additionally, changes in soil microbial communities due to climate stress may affect the limited biodegradation of certain plastics, though the net effect on conventional polymers is likely negligible (Yaghoubi Khanghahi *et al.*, 2026).

Crucially, MPs themselves may influence climate feedback loops. Recent studies suggest that MPs can affect soil carbon sequestration by altering microbial decomposition of organic matter (Liu *et al.*, 2024). By disrupting fungal networks and bacterial activity, MPs may reduce the stability of soil organic carbon, potentially weaken soil carbon storage and altering greenhouse gas fluxes (Liu *et al.*, 2024). This potential positive feedback loop, where plastic pollution exacerbates climate change, which in turn accelerates plastic fragmentation, represents a significant but underexplored risk in global environmental models.

Risk of Critical Stress Thresholds

The cumulative increase in soil MP loads has raised concern that terrestrial ecosystems could eventually approach critical stress thresholds. However, such thresholds have not yet been quantitatively established for most soil functions, and current evidence remains insufficient to define universal concentration limits. Existing knowledge therefore supports the concept of potential ecological tipping points rather than confirmed threshold values. One potential tipping point is the disruption of key soil microbial networks responsible for nutrient cycling. If MP concentrations exceed critical thresholds, they may inhibit the activity of nitrogen-fixing bacteria, mycorrhizal fungi, and decomposers, leading to reduced soil fertility and increased dependency on synthetic fertilisers (de Souza Machado *et al.*, 2019; Han *et al.*, 2024). This creates a vicious cycle where degraded soils require more inputs, further exacerbating environmental stress.

Another tipping point involves soil matrix physical integrity. High concentrations of MPs can alter soil porosity, water retention, and aggregate stability, potentially leading to increased erosion and reduced water infiltration (OECD, 2022b; Sajjad *et al.*, 2022). In agricultural systems, this could result in significant yield losses, threatening food security in regions heavily reliant on plastic-intensive farming practices (UNDP, 2021). Furthermore, the trophic transfer of MPs through soil food webs may lead to population declines in key soil fauna such as earthworms and collembola, disrupting ecosystem engineering processes and biodiversity (Guo *et al.*, 2023; X. Zhang *et al.*, 2025).

In summary, the trajectory of terrestrial MP pollution under BAU scenarios is alarming. If current production and environmental leakage trends continue, soils worldwide are likely to experience substantially greater plastic accumulation by the middle of this century, with increasing pressure on biodiversity, soil functioning, and ecosystem services. The combination of rising production, legacy fragmentation, climate interactions, and potential tipping points underscores the urgency of preventive action. Remediation alone is insufficient; the focus must shift to reducing plastic inputs at the source, improving waste management, and developing sustainable alternatives that do not contribute to long-term soil accumulation. The following sections will explore the knowledge gaps that hinder accurate projection and the pathways forward to mitigate this silent crisis.

Taken together, published global scenarios consistently suggest that terrestrial microplastic contamination is likely to increase under business-as-usual conditions. Nevertheless, considerable uncertainty remains regarding the magnitude, timing, and ecological consequences of future accumulation because long-term field observations, standardised monitoring networks, and validated predictive soil models remain limited. Future projections should therefore be interpreted as plausible trajectories based on current knowledge rather than precise forecasts.

Conclusions

The accumulation of MPs in terrestrial ecosystems represents an increasingly important environmental challenge with implications for soil functioning, agricultural sustainability, and ecosystem resilience. Unlike aquatic systems, where plastic pollution is highly visible and extensively monitored, terrestrial environments receive substantial and increasingly recognised plastic inputs from agricultural activities, waste-management practices, atmospheric deposition, and urban sources. As a result, soils have emerged as major long-term reservoirs of plastic contamination, where particles can persist, fragment, and interact with complex biological and physicochemical processes.

The evidence reviewed in this perspective suggests that current contamination levels may represent only the early stages of a much larger accumulation process. Published global scenarios consistently suggest that, under business-as-usual scenarios, global plastic production is projected to exceed 1.2 billion tonnes annually by 2060, accompanied by continued increases in plastic waste generation, environmental leakage, and secondary microplastic formation. These projections indicate that terrestrial ecosystems will likely experience sustained and potentially accelerating MP accumulation over the coming decades, raising concerns regarding soil biodiversity, nutrient cycling, plant productivity, and other ecosystem services that underpin food production systems.

Despite the substantial progress achieved during the past decade, major uncertainties remain regarding long-term accumulation rates, ecological thresholds, interactions with soil biota, plant responses, and the persistence of legacy plastic stocks already present in terrestrial environments. Addressing these uncertainties will require a transition from predominantly descriptive studies toward predictive and process-based research. Particular emphasis should be placed on the establishment of coordinated global monitoring networks, the generation of long-term datasets across diverse climatic and land-use systems, and the development of robust models capable of forecasting future contamination trajectories and identifying ecological tipping points.

Ultimately, addressing terrestrial microplastic pollution will require coordinated efforts across research, policy, industry, and agricultural sectors. Future progress should prioritise five complementary actions: (i) Establishing standardised global monitoring networks capable of generating harmonised long-term datasets; (ii) conducting environmentally realistic long-term field experiments to identify ecological thresholds and ecosystem responses; (iii) developing robust predictive models that integrate plastic production, environmental leakage, fragmentation dynamics, and climate-change interactions; (iv) implementing effective source-prevention strategies through improved plastic management and circular-economy practices; and (v) accelerating the development, field validation, and life-cycle assessment of genuinely sustainable alternative materials. Together, these priorities will strengthen the scientific basis for evidence-informed policies aimed at protecting soil health, maintaining agricultural productivity, and safeguarding the long-term sustainability of terrestrial ecosystems.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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