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REVIEW

Microplastics in Terrestrial Ecosystems: Detection, Transport Pathways, and Ecotoxicological Risks

Xueli Han [1*], ***Zhiqiang Wang*** [2]

[1] *Shandong Vocational College of Science and Technology, Weifang 261053, China*
[2] *Shandong Meiling Zhonglian Environmental Engineering Co., Ltd., Zibo 255000, China*

ABSTRACT

Microplastics are becoming well-known as chronic pollutants of terrestrial ecosystems, although their sources, dynamics of transportation, reliability of detection and ecological hazard are not evenly described. This review is a synthesis of the existing information about microplastics in soils, including analytical detection and characterization techniques, the major sources in the terrestrial environment, transport routes within the compartments and between compartments, and reported ecotoxicological consequences on soil biota, plants, and microbial communities. We also critically discuss the strengths and weaknesses of methodologies, making the distinction of sampling design differences, size detection limits, polymer identification methods, and quality assurance procedures on data comparability and uncertainty. An important outcome of this review is the systematic evaluation of the strength of evidence in three interrelated areas: measurement, environmental transport, and biological impacts, hence explaining which findings are strong and in which areas of research significant knowledge gaps still exist. We also suggest a conceptual framework that strongly connects the measurement uncertainty to the exposure estimation, interpretation of risk, and management relevance. This review uses mechanistic insights into transport and ecotoxicology alongside analysis constraints to add to the more comprehensive foundation of terrestrial risk assessment. Lastly, we determine research priorities, such as harmonized methodologies, realistic exposure scenarios, and cross-scale monitoring strategies, in order to assist in the science-based policies and mitigation action.

Keywords: Microplastics; Soil; Transport Pathways; Detection Methods; Ecotoxicology

*CORRESPONDING AUTHOR:
Xueli Han, Shandong Vocational College of Science and Technology, Weifang 261053, China; Email:418764870@qq.com

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1. Introduction

The production and consumption of plastics have grown at an alarming rate in the past few decades, allowing the major benefits of plastics to include food preservation, healthcare, and industrial efficiency, but it has also introduced lasting streams of garbage, which break down and spread throughout the environment [1]. Although oceans have traditionally been the focus of the study of the phenomenon, an increasing number of studies are recognizing terrestrial ecosystems, notably soils, as one of the largest long-term repositories of plastic debris, and receiving inputs from agriculture, urban processes, industry, and the atmosphere. Land systems in most areas are continuously fed by plastics (e.g., plastic mulching, compost/manure, sewage sludge/biosolid reuse, tires/road wear, textile fiber emissions). Once introduced, these materials progressively fragment into microplastics (commonly defined as plastic particles <5 mm) and potentially nanoplastics (typically <1 μm or <1,000 nm, depending on the operational definition). This contrasts with highly dynamic aquatic systems, where the particles are likely to be washed quickly to the coastal sinks; soils can hold on to the plastics over an extended period due to aggregation, burial, and physical covering within the soil structure, forming an environment of chronic exposure of soil organisms and redistribution with every erosion and resuspension of the atmosphere [2,3].

Terrestrial microplastic pollution does not merely represent a natural continuation of the marine issue; it has its own sources, physical environments, and ecological impacts. Soils are complex structures, chemically reactive, and biologically active matrices, whereby particles are engaged to minerals, organic matter, pore water, and high-density biota. These environments cause plastics to be subjected to mechanical abrasion, photo-oxidation at the surface, and colonization by microbial biofilms, which modify their density, surface charge, brittleness, and sorptive behavior. Such alterations may affect transport (e.g., aggregation retention as opposed to migration by preferential flow routes) and bioavailability (e.g., ingestion and soil invertebrate retention). Besides, soil ecosystems facilitate processes that are core to ecosystem services and human health, including nutrient cycling, carbon sequestration, water management, and crop yields, so it is imperative to establish whether microplastics pose a direct or indirect threat to these processes [2,4,5].

The greatest difficulty in bringing the literature on terrestrial microplastics together is that the evidence can be found scattered across various disciplines that tend to adopt different conceptual and methodological approaches. Occurrence, polymer identification, and analytical reliability are stressed by environmental chemists; soil scientists by aggregation, hydrology, and land management controls; ecotoxicologists by organism responses and mechanistic endpoints; and agronomists by soil health and food production. These perspectives are complex to integrate due to the variability in the definition and measurement of microplastics, reporting of results, and construction of exposure scenarios. It can be illustrated by the fact that field surveys can specify the abundance as particles per kilogram of dry soil, but some laboratory studies specify dosing by mass, size detection limits vary over orders of magnitude depending on the technique deployed (microscopy, Fourier-transform infrared spectroscopy (FTIR)/Raman spectroscopy, thermal), and control of contamination (particularly of fibers) varies widely. The differences restrict the ability to compare studies and create effective risk assessments and risk management policies [6].

Detection and characterization are more fundamental concerns since that which is not accurately measurable cannot be accurately modeled or controlled. Filamentous and organic fractions, biofilms, and clay-rich or humic soils in general make soil a rather challenging matrix to analyze. Microplastic particles are fixed onto organic and mineral fractions, biofilm can mask surfaces, and a clay-rich or humic soil can interfere with spectroscopes. Usually, the extraction process is based on the use of density separation and digestion, which should balance between an organic matter removal method and retention of the polymer surface. Although particles were isolated, it is not very easy to identify the polymer in an accurate manner. At the particle level, Fourier-transform infrared spectroscopy (FTIR) and Raman microscopy are able to offer polymer-level confirmation, but are limited by size, fluorescence, and throughput. Pyrolysis and other thermal methods, e.g., pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS), can measure the mass of polymers and occasionally additives in complex samples but lose measures of particle structure, size, and shape, which may be very important to the biological interactions. Consequently, there is confusion between high and less confident polymer identifications and visual classifications in the literature, and there are also large differences in reporting conventions. In this regard, the option of methodology, quality assurance/quality control (QA/QC), and standardized reporting is approached in this review as the key aspects of any significant synthesis of terrestrial occurrence and risk[7,8].

In addition to measurement, knowledge of transport pathways is the key to predicting the location of microplastic accumulation and the exposed organisms. The terrestrial microplastics have various prevailing sources, which vary in the type and behavior of the particles. Agricultural plastics typically include films and fragments of mulching and greenhouse plastics, and compost and manure may provide a complex blend of fibers and fragments, seen to be sources of upstream waste handling and consumer. City settings are sources of textile fibers, waste packaging, construction-related materials, and, most importantly, road-related debris such as tire and road wear particles, which can constitute a significant portion of near-road microplastic-like particulates. Microplastics are able to be introduced to far corners of the atmosphere by atmospheric deposition, and soil and atmosphere are closely coupled by the processes of deposition and resuspension, respectively. As soon as microplastics get ashore, they can be laterally moved through runoff and erosion, deposited in areas, and carried towards river systems. Bioturbation (e.g., earthworm activity), root development, shrink–swell processes, and selective transport along cracks and macropores are the ways the particles can be redistributed vertically. These processes have a relative significance based on the properties of particles (size, shape, density, surface roughness), soil properties (texture, structure, organic matter, moisture regime), and land management activities including tillage, irrigation, and erosion control[9–11].

The ecotoxicological risk in the terrestrial ecosystems arises as a result of the overlap of the exposure and hazard. The exposure is universal and multi-pathway: in the case of soil: soil via ingestion by invertebrates, soil via ingestion by detritivores and predators, soil via translocation through the trophic chains, rhizosphere as plants and associated microbiomes are exposed to particles in the rhizosphere; by ingestion: in the case of vertebrates, ingestion of microplastics may occur directly through soil, dust, water, and prey. A variety of effects, such as altered feeding, growth, and reproduction; altered burrowing and avoidance behavior; biomarkers of oxidative stress and inflammatory-like responses, have been reported using laboratory experiments, but the environmental applicability of most experiments is controversial due to such unrealistically high concentrations, pristine particles that do not reflect the field aging, and poor representation of the predominant types of particles found in the environment, such as fibers, films, and tire-wear-associated materials. In addition, the terrestrial ecosystems are naturally prone to co-stressors (e.g., drought, heat, salinity, pesticide combinations, nutrient enrichment), and microplastics can either increase or decrease such stressors, altering the physical properties of soils (e.g., aggregation, water retention) or the functioning of the microbial community. Finally, risks are not to be evaluated only based on the impacts on the soil processes that constitute the foundation of the ecosystem services[12,13].

To guarantee transparency and analytical rigor, this review is based on a systematic and evaluative approach to literature synthesis. A keyword-based search of the large scientific databases with combinations of keywords pertaining to terrestrial microplastics, detection techniques, transport processes, and ecotoxicological effects was used to identify the relevant peer-reviewed studies. The focus was made on studies published in the last decade, though, where conceptually vital, seminal older studies were included. The evaluation of evidence was done on a comparative basis and was also evaluated on the basis of methodological soundness, sample size, environmental realism, analytical resolution (e.g., size detection limits, polymer confirmation), and quality assurance practices. In detection, transport, and biological effect investigations, we discuss the strength and consistency of the evidence, are able to determine sources of uncertainty that repeatedly arise, and separate well-supported conclusions and emerging or speculative ones. This evaluative view can bring the review to a further step beyond the summary to critical integration and risk-relevant interpretation. The review aims to contribute to the creation of realistic exposure science and transport modeling to provide support to the development of credible terrestrial risk assessment models and informed interventions to safeguard soil health and the ecosystem services on which human societies rely[14,15]. The conceptual structure of this review linking sources, compartments, transport, exposure, effects, and management is illustrated in **Figure 1**.

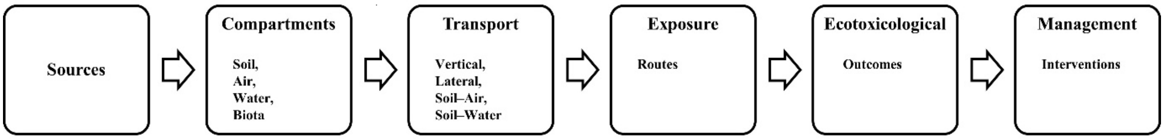

Figure 1. Graphical overview of the review framework.

2. Microplastics: Exposure and Ecotoxicological Risks

On land, there exist a variety of biological communities and multifaceted physicochemical interfaces that define the availability of the microplastics (MPs) to organisms and how risks will eventually be realized[16]. MPs are present in soils with mineral particles, organic matter, pore water and abundant biota, and the behavior of these particles is influenced by particle properties (size, shape, polymer type, density and aging state), soil properties (texture, structure, pH, organic carbon, moisture regime), and land management (tillage, irrigation, amendment inputs). Here, a synthesis of the existing knowledge of the exposure routes in terrestrial biota, the main ecotoxicological endpoints that have been identified so far, and the mechanistic pathways that have received the most consistent support by evidence is provided, with uncertainties that complicate extrapolation of risks in the laboratory setting to conditions in the field[17].

2.1. Conceptual Distinction between Hazard and Ecological Risk

Increasing data has been linked to microplastics in terrestrial ecosystems on both biological effects and impact. Nonetheless, these findings have to be interpreted with a clear differentiation between hazard and risk. Hazard is defined as the innate ability of microplastics to induce negative biological outcomes at a specified exposure parameter, which is usually revealed in controlled laboratory experiments[18,19]. Risk, on the other hand, indicates the likelihood of occurrence of such negative effects in realistic conditions of environmental exposure, taking into account concentration, particle attributes, periods, and ecological setting. Analytically, to understand terrestrial microplastics, ecotoxicology studies may be divided into three levels:

(1) **Laboratory Hazard Studies**

These studies normally entail controlled exposures in artificial and simplified soil matrices, often of microplastics of purified materials at concentrations that are possibly higher than most of the reported concentrations in the environment. The exposure periods are usually short-term to medium-term. These investigations are useful in offering a mechanistic understanding but mostly show the potential of hazard as opposed to risk, which is confirmed by the environment[20].

(2) **Soil-Based or Mesocosm Studies**

In such studies, more realistic soil matrices are used, occasionally aged or collected from the environment, and occasionally, multi-species interactions. They are providing better ecological shape than laboratory assays, but are also partly controlled. These experiments justify context-specific effect measurements but might not be reflective of variation in the exposure of the landscape.

(3) **Field Observations and Monitoring-Based Studies**

Field-based studies determine organisms or ecological functionality at the naturally present microplastic levels. Such studies are highly ecologically realistic but also fail to cause inference because of co-occurring stressors and confounding environmental factors. At present, this kind of research is relatively limited in land-based systems. In these levels, the levels of evidence tend to diminish towards ecological realism, which is a trade-off between the experimental control and the complexity of the environment. This trend has to be taken into consideration when understanding the ecological meaning[21].

2.2. Exposure Routes across Key Terrestrial Receptors

2.2.1. Soil Invertebrates

Invertebrates that feed on soil or detritus are also one of the taxa most directly exposed, as many will ingest soil or detritus during normal feeding. The receptors of special interest are the earthworms, because they ingest a lot of soil, burrow, and reorganize the soil. The MPs may be consumed by soil and organic matter, held in the gut, and expelled in casts, and may repurpose the particles into the aggregates and deeper layers. Collembola and mites feed on organic debris and microbial biofilms, which may augment contacts with MPs that have been covered with organic matter (eco-corona). Nematodes can digest smaller particles, and they are also vulnerable to fluctuation in microbial community changes and the chemistry of pore water[22].

The intensity of exposure is related to habitat use and feeding guild. Surface-associated organisms (epigeic) will have access to recently deposited fibers and pieces, whereas vertical movement is possible for endogeic/anecic organisms. Ecological relevance is enhanced by laboratory exposure designs that are similar to the realistic feeding modes (soil-based instead of aqueous suspensions)[23].

2.2.2. Plants and the Rhizosphere

Plants are exposed mostly at the root, soil interface, where roots are exposed to particles in the rhizosphere, and at the soil microbes and exudates that can be used to alter the surfaces of particles. The possible plant effects are (i) physical effects which influence penetration of roots and soil aggregation, (ii) water retention and aeration, and (iii) nutrient availability and microbial activity. Very fine particles (submicron range) are most likely to be reported to undergo internal uptake and translocation, and generally only rely heavily on experimental labeling and control of contamination. In the case of Science Citation Index (SCI)-standard synthesis, one should differentiate (a) solid evidence of rhizosphere-scale interactions and growth effects, and (b) fewer solid claims of broad-scale internalization, which could be confounded by particle adherence to root surfaces, imaging artifacts, or background contamination[24].

2.2.3. Soil Microbial Communities

In certain studies, microplastics offer long-term surfaces for microbial colonization, forming a plastisphere that is independent of the microhabitats of the adjacent soils. This has two implications: (i) MPs can serve as islands of microhabitat, and remodel the microbial community at that spot, and (ii) MPs can also have an effect on functional processes (enzyme activities, carbon use efficiency, nitrogen transformations) by modulating substrate availability, moisture micro gradients, or redox conditions. The plastisphere effects are likely to be shifted into functional change at the ecosystem scale, with reliance on particle abundance, aging condition, and particle integration into aggregates where microbial activities are concentrated[25].

2.2.4. Vertebrates and Terrestrial Food Webs

Exposure to vertebrates occurs by accidental ingestion of contaminated soil, ingestion of contaminated invertebrates and plant food, and by ingestion of dust during grooming or feeding. There may be increased exposure in birds foraging in agricultural areas and mammals living in roadside/urban-proximate areas. Food-web transfer: Food webs are plausible in which accumulation of particles in the gut of prey items occurs, although there is little evidence of biomagnification in terrestrial systems that may be related to particle size and retention time. Trophic transfer is therefore to be looked at keenly as part of the exposure pathway, without exaggerating biomagnification, without powerful supporting data[26,27]. Major receptor groups, exposure routes, and dominant effect pathways are integrated in **Figure 2**.

2.3. Ecotoxicological Endpoints Used in Terrestrial Microplastic Studies

Terrestrial MP ecotoxicology represents a wide spectrum of endpoints, and they can be classified according to the levels of biology. These scales are organismal, physiological and biochemical, and community and functional, which are all insightful on the impacts of MPs on the ecosystems.

Ecotoxicological endpoints at the organismal level are survival, growth, reproduction, development time, and behavioral reactions. In particular, the cocoon production is used as a measure of reproduction in earthworms, and fecundity is frequently used in collembolans. Negative behavioral changes like avoidance, burrowing, and feeding activity are also demonstrations of the effects of MP exposure that assist researchers to learn how organisms are adjusted or how they respond to pollutants. Physiological and biochemical reactions to MP pollution have a variety of indicators of oxidative stress, antioxidant enzyme activity, lipid peroxidation, and detoxifying enzyme induction. The biomarkers are important in the evaluation of cellular interference and the physiological outcome of the pollutants. Also, in larger invertebrates, energy stores and gut histopathology have been found to be viable indicators of the overall effects of MPs on individual health and functionality[28].

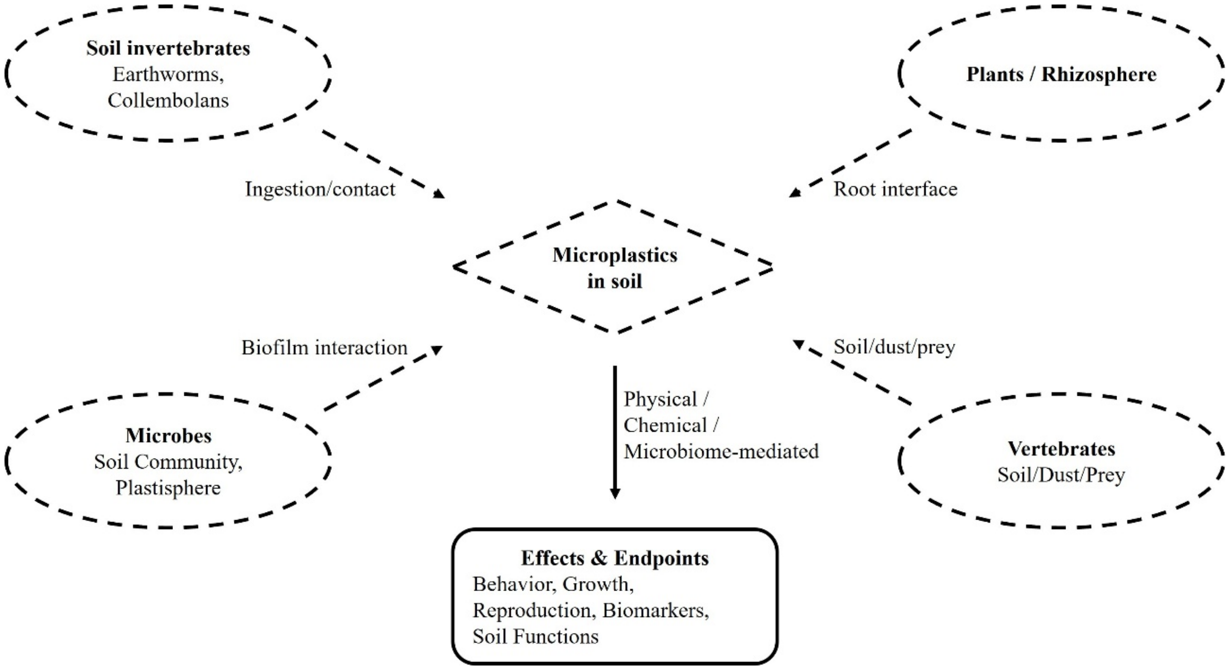

Figure 2. Exposure routes and effect pathways across terrestrial receptors.

Community and functional endpoint MP exposure may cause changes in the microbial composition of soils, alterations in the enzyme activity, and alterations in litter decomposition velocity, which are critical to nutrient cycling and soil health. The metrics of soil respiration and nitrogen cycles can also serve as valuable data relating to the functioning of the ecosystem, whereas the alterations in the soil aggregation and porosity influence the quality of the habitats, which complement the effects of MPs on the environment to a greater extent.

The most policy-relevant evidence uses realistic exposure conditions and outcomes with significance to ecosystem functionality, including decomposition and nutrient cycling, and population sustainability, using such measures as reproduction. This method is not confined to the use of sensitive biomarkers whose meaning may be hard to discern alone, but rather the focus is on a comprehensive interpretation of environmental health[29,30]. A cross-taxa summary of exposure routes, endpoints, and recurring study limitations is provided in **Table 1**.

Table 1. Summary of ecotoxicological evidence and endpoints by receptor group.

Receptor Group	Dominant Exposure Routes	Common Endpoints Reported	Typical Experimental Context	Key Realism Gaps to Flag in a Review	Weight-of-Evidence (Qualitative)
Earthworms	Soil ingestion; burrowing contact	Growth, reproduction, burrowing/avoidance, biomarkers	Soil spiking; short to chronic	Often pristine particles; limited aging; concentration realism varies	Moderate (good test systems, but realism varies)
Collembola/ mites	Detritus feeding; surface soil contact	Reproduction, survival, behavior	Soil-based assays	Underrepresentation of fibers/films; limited co-stressor contexts	Moderate
Nematodes	Ingestion of small particles; pore-water interface	Development, reproduction, stress biomarkers	Agar/soil microcosms	Nanoplastics often hypothesized but rarely quantified; exposure verification needed	Low–moderate
Soil microbial communities	Colonization of particles; exposure to eco-coronas/additives	Community shifts, enzyme activities, respiration/N cycling proxies	Microcosms; amendment studies	Difficult attribution (MP vs. co-delivered organics); functional endpoints inconsistent	Moderate (for community shifts), low–moderate (for ecosystem-scale function)

Table 1. *Cont.*

Receptor Group	Dominant Exposure Routes	Common Endpoints Reported	Typical Experimental Context	Key Realism Gaps to Flag in a Review	Weight-of-Evidence (Qualitative)
Plants/ rhizosphere	Root–particle interaction; rhizosphere changes	Germination, growth, nutrient status, rhizosphere changes	Pot studies; spiked soils	Internalization claims method-sensitive; often limited aging and realistic morphologies	Low–moderate
Insects (larvae/adults)	Soil contact; ingestion via detritus/prey	Growth, development time, behavior	Soil/diet exposures	Particle type realism inconsistent; limited multigenerational work	Low–moderate
Vertebrates (where studied)	Incidental soil/dust ingestion; prey-mediated	Body condition, biomarkers, gut effects	Field observations; limited lab	Sparse terrestrial datasets; difficult source attribution	Low

2.4. Mechanisms of Toxicity and Indirect Effects

2.4.1. Physical Mechanisms

The physical effects include filling of the gut, abrasion, and decreased feeding efficiency, particularly of fibrous particles. In soils, MPs can have an impact on the physical environment as well: alteration of the physical properties of soils, such as changes in aggregation, bulk density, porosity, and water retention, can indirectly influence the performance of organisms by modifying the habitat structure and water availability. These indirect routes are especially relevant to terrestrial systems, where the microclimate and pore structure are used to control the diffusion of oxygen, microbial activity, and the availability of resources[31].

2.4.2. Chemical Mechanisms: Additives and Co-Contaminants

Plastics do have several additives, which include plasticizers, stabilizers, and pigments, which can leach under soil conditions. Secondly, MPs can absorb organic pollutants and metals that already exist in the soil. The optical effect of MPs on the bioavailability of these co-contaminants depends on a number of factors, which include soil organic matter, pH, ionic strength, and the aging condition of the MPs. Moreover, the gut chemistry of organisms may also have a role in the promotion of desorption and hence the release of these pollutants.

There are two major mechanisms that should be discussed in the context of the review. The former deals with additive leaching of the plastic matrix, and it can happen without the presence of sorbed pollutants. The effect of this process depends on the chemical characteristics of the additives and the environmental factors that facilitate dissolution of the additives from the plastic structure. The second process is that of the vector effects, whereby the MPs become a means of external contaminants. They are complex and context-dependent and are strongly sensitive to the different environmental circumstances, as well as biological factors[32].

2.4.3. Biofilm and Eco-Corona Effects

The formation of biofilms alters the surface of particles, which in most cases makes them more hydrophilic and allows aggregation with minerals and organic matter. In the case of organisms, biofilms may enhance palatability or modify the probability of ingestion (particles appear as food), which may expose them to higher exposure. Biofilms can also harbor microbial taxa that have different functional potential within the surrounding soil, particularly affecting microbe-microbe and microbe-host interactions[33].

2.4.4. Mixture Toxicity and Co-Stressor Interactions

On Earth, living beings hardly encounter MPs alone. Microplastic impact can also respond to the drought, temperature variations, salinity, exposure to pesticides, and nutrient enrichment. As an example, when MPs alter the soil water retention, they can reduce or increase drought stress depending on the context; when MPs absorb pesticides, they can change exposure kinetics and not just enhance toxicity. The standard use of co-stressors should be highlighted in SCI-standard synthesis, as they are necessary for ecological realism, and the direction of interaction (synergistic or antagonistic) cannot be presupposed[34].

2.5. From Hazard to Risk: Interpreting Evidence Strength

The long-standing issue in the subject of MP ecotoxicology has been the disconnect between laboratory dosing regimens and the concentration and nature of particles in the natural environment. Most experiments are conducted using pristine spherical beads due to experimental convenience, but this is not a realistic representation of the various forms of MPs found in the environment, which are mostly in the form of fibers, films, irregular fragments, and traffic-derived particles, which are usually aged and biofilm-coated. This mismatch may have a drastic effect on the transport characteristics as well as the toxicity of MPs in the natural environment. Strong evidence can be increased when the studies consider environmentally realistic particle type and size distributions[35]. Aging and weathering interventions also enhance the applicability of the laboratory conditions since the interventions simulate the environmental variations experienced by MPs with time. Also, exposure matrices based on soil are used in such a way that the studies are closer to the natural medium by which MPs are exposed to organisms. Priority should be given to chronic and reproductive endpoints because they give more detailed information on the ecological impacts over the long term. The next important fact is that concentrations must be reported in such a way that they can be compared with field surveys, preferably with the counts of particles and their mass, as well as their size ranges, should be defined[36].

In case these criteria are not fulfilled, the findings of such studies must be interpreted as an indication of the possible dangers, but not the quantitative estimations of risks. Poor experimental conditions can restrict the generalizability of results to real-life situations, and more realistic study designs are necessary to enhance the ability to assess the ecological risks of MPs in natural settings.

2.6. Synthesis: Current Evidence Strength and Research Gaps

Collectively, existing on-land ecotoxicological data allow us to conclude that microplastics can pose a hazard to a variety of receptor categories under controlled exposure conditions. Physiological and behavioral responses at an individual level are always recorded through laboratory studies. Nevertheless, hazard-to-ecological risk translation remains limited due to a range of factors: uncertainty regarding environmental exposure concentrations, lack of long-term and multigenerational research, inadequate field testing, and differences in particle characterization methodology[37].

There is limited evidence of impairment of populations or ecosystems on a large scale at the level of the population or the entire ecosystem in terrestrial environments. Most of the reported results are based on mechanistic plausibility as opposed to established environmental risk in realistic exposure conditions. Hence, it is justifiable to be careful in the extrapolation of laboratory-based hazard data to the ecological measures at the landscape scale.

The future needs to focus on designs of exposure that are more environmentally realistic, long-term field validation, harmonization of methods, and any linkage of the measured environmental concentrations with biological thresholds. Such integration is the only way to transform the hazard-based knowledge into sound terrestrial risk assessment[38].

3. Detection and Characterization

Any defensible evaluation of microplastics (MPs) in the terrestrial environment is supported by reliable detection and characterization. Unlike aquatic media, soils and other terrestrial media have large, random loads of minerals and organic matter, are highly aggregated and have detailed microstructure, and are highly spatially variable over short distances. These characteristics make them difficult to extract, add to analytical interferences, and exaggerate the effects of non-uniform sampling and reporting. Another complication is the almost omnipresence of contamination, especially cited airborne synthetic fibers and plastic consumables during the sampling and laboratory processing[39–41]. Consequently, the differences between studies are usually manifestations of differences in sampling design, pretreatment decisions, recovery effectiveness, size detection limits, polymer confirmation techniques, and QA/QC rigor as opposed to the actual variability of the environment. The materials of this section summarize the existing best practices in sampling, preparation, identification, quantification, and harmonization, and highlight new methods that attempt to overcome long-standing challenges like quantification of tiny microplastics and nanoplastics in complex soil matrices[42].

3.1. Sampling Design in Terrestrial Systems

3.1.1. Defining the Target Matrix and Sampling Domain

One of the main origins of inconsistencies in the terrestrial MP research is the definition of the target matrix. Soil can imply litter layer, organic horizons, mineral topsoil, rhizosphere soil, deeper subsoil, or combinations or mixtures of these compartments, each with varying organic content, particle binding, and is probably a source of microplastics. The review of the studies related to the SCI-standard should focus on the fact that the studies should provide a clear definition of the studied matrix and the sampling domain, with the depths of the study and an explanation of why they are selected. In most landscapes, the inputs are maximum at the surface, although these can be redistributed to lower strata by biological mixing and preferential flow, so the sampling depth must be equalized with the intended purpose of the review, such as characterizing the sources, quantifying exposure at the root zone, or long-term storage in the subsoils. Similarly, land use and management settings should be defined by the sampling design since these usually define predominant sources and particle morphologies, e.g., films in plastic-mulched farmlands, fibers in urban and atmospheric-deposition settings, and traffic-generated particles around roads[39].

3.1.2. Replication, Spatial Heterogeneity, and Temporal Coverage

On land, MP distribution can often be patchy, with a lot of within-site variability due to microtopography, vegetation cover, agricultural activities, localized inputs, and edge, drainage, or depositional preferences. Replication is also not a statistical nicety but a condition for interpretable site-level estimates. Extensive designs are often multicore and composed of composite sampling plans that combine a number of subsamples to sample a plot or land-use unit. Gradient stratified sampling based on the probable influence of sources, e.g., distance to roads or within-field management zones, assists in separating spatial controls and methodological noise. It may also matter whether the temporal coverage is such that the processes of deposition, runoff, erosion, and agricultural activity are seasonal in those areas; sampling across contrasting seasons or before and after significant events (e.g., harvest, heavy rainfall) may be informative of short-term mobilization or redistribution otherwise invisible at a single time-point[43].

3.1.3. Sample Handling and Storage

The handling of the post-collection can also change the apparent concentrations and the properties of the particles due to loss of fine fraction, changes in aggregation, or contamination. Normalization of mass is usually required to be consistent, although even drying method and temperature have the potential to affect aggregation and extraction behavior, and long-term storage in plastic containers can increase the risk of contamination. Careful reporting must then contain container material, storage conditions and time, drying regime, and measures that are implemented to reduce particle loss. Due to the most common use of microplastics per unit dry mass, the determination of moisture and processes involving large debris or stones should be recorded so that the normalization will be similar and comparable[44].

3.2. Contamination Control and QA/QC

This is of particular concern to terrestrial MP research due to the possibility of fiber fallout and plastic tools adding signals that are similar or even higher than actual environmental contamination, particularly low-contamination reference soils. SCI-standard methodology considers QA/QC as part of the analytical process and not a supplementary test. Exposed field blanks at the time of sampling receive atmospheric deposition and handling contamination, and the procedural blanks are used to measure reagent, filter, and laboratory contamination. Airborne controls are useful when the laboratories are performing major processing operations, since even in a well-controlled lab setting, the introduction of synthetic fibers is possible. In addition to the blanks, to measure the efficiency of extraction and how much soil texture and organic content, or digestion stages, can bias the recovery of different fibers, films, and fragments, spiked recovery tests are necessary[45,46].

3.2.1. Field and Laboratory Controls

Laboratory as well as field controls must be made to represent every process step. Field blanks are most informative when the blanks undergo the same exposure time and handling as actual samples, such as tool contact and container opening. The laboratory procedural blanks must contain all the reagents, digestion procedures, density separation, filtration, and mounting procedures that are applied to the samples. Because contamination is usually dominated by fibers, laboratory clothing, airflow conditions, and filtering the air or using clean hoods or a filtered air environment, these factors are significant to be documented to be interpreted. It is not just the presence of blanks that makes the conclusions in a study strong, but it is also necessary that blank results are reported and utilized in corrections in a transparent manner[47].

3.2.2. Reporting Blank Corrections and Recoveries

Full disclosure implies that missing loads, recovery rates and detection limits should be clearly presented. In their absence, it is hard to estimate whether reported concentrations are over-contaminant background or whether or not extraction methods are biased to recover under certain classes of particles. Recovery needs to be considered in model polymers and morphologies and, hopefully, within the range of size fractions of interest since recovery of smaller particles typically decreases, and fibers may go through filters or stick onto vessel walls. The limit of detection (LOD)/limit of quantification (LOQ) statements must indicate the complete procedure, such as blank variability and size of minimal particles, as opposed to instrument sensitivity itself. The method employed to correct the blanks should be described in detail, such as whether it was calculated as the total counts, individual morphology, or as individual polymer types, where polymer identification was carried out[48].

3.3. Sample Preparation and Extraction from Soil Matrices

The preparation of the sample is aimed at separating MPs of mineral and organic materials and maintaining particle morphology and the type of polymer. Soils make them difficult to extract since microplastics may be entrained in aggregates, covered by organic matter and biofilms, and electrostatically or physically attached to clay minerals. In line with this, extraction is hardly a one-step process; rather, it is usually a composite of disaggregation, size fractionation, density separation, digestion, and filtration. Every step presents a trade-off between recovery, polymer preservation, throughput, and risk of contamination, and these trade-offs ought to be clearly tackled when comparing study results[49].

3.3.1. Drying, Disaggregation, and Sieving

The process of drying and disaggregation defines the processes of liberation of microplastics in aggregates or entrapment and underestimation of aggregates. Light disaggregation may raise recovery without excessive fragmentation; however, excessive aggressiveness may cause larger particles to be broken into plastic fragments and produce spurious inflation of small particle counts. Sieving is also broadly employed to specify the classes of the operational size as well as to concentrate the study power where the identification process is most valid. The selection of sieve cutoffs, however, has a strong influence on the results, since a study that only covers large fractions can lose the numerically dominant pool of small particles, whereas a study of very small fractions has a substantially larger risk of interference and misidentification. Clear records of size ranges that are stored and examined are thus essential in the interpretation of disparity between datasets[50].

3.3.2. Density Separation

Density separation relies on the dissimilarity between the polymer and mineral density, though its accomplishment is based on the density of the solution, the viscosity of the solution, and the particles' morphology and composition of soil. Low-density solutions will efficiently recover polyolefins, but poorly recover higher-density polymers (and higher-density solutions will improve the range of recovery at the sacrifice of viscosity and handling complexity). Fibers are a unique problem as they may entangle with organic debris or create flocs that may act as mineral particles. Plastics may be entrapped by fine clays and humic materials and inhibit the flotation process, restoring the removal process to multiple separations or dispersant treatments. Since the separations and settling times affect the recovery and the contamination probability, they ought to be standardized in research, and these parameters must be reported with good detail so that they can be replicated[51].

3.3.3. Organic Matter Removal: Chemical and Enzymatic Digestion

Removal of organic matter increases the identification by minimizing spectral interferences and visual confusion. However, chemical oxidation or alkaline digestion can be useful but can ruin some polymers or surface change, or eliminate additives in a manner that can alter both the identification spectra and the particle properties. Enzyme digestion can be less vigorous and polymer integrity can be preserved; however, it is slower, more costly, and inconsistent between different types of heterogeneous soil organic matter. Polymer-specific stability testing and recovery testing under the conditions of the precise digestion under which the choice of method is to be used should be validated. In order to do the review synthesis, one must draw a line between the studies that report polymer preservation and recoveries or studies that do not, so that the losses caused by digestion could be perceived as actual ecological differences[52].

3.3.4. Filtration and Sample Mounting

Particles are captured by filtration and then collected to perform microscopy and spectroscopy; however, the filter medium and the size of the pore affect recovery and downstream compatibility. Other filters report spectral backgrounds, which make FTIR or Raman analysis difficult, whereas others can be blocked easily when soils have fine residues, resulting in the loss of particles or uneven distribution of particles. Supporting and processing processes may also be biased by morphology counts by fiber loss or fragmentation. These should be reported in detail, with the type of filter, pore size, filtration strategy, and method of mounting filters, and precautions to prevent cross-sample carryover and deposition of air during drying and storage of filters[53].

3.4. Identification Methods: Confirming Polymer Type

The necessity to differentiate between microplastics and natural particles and to attribute the sources and assess the risks requires accurate polymer identification. Visual classification is usually not very reliable in soils because soils contain organic fibers, soot, and mineral grains that resemble plastic morphology. SCI-standard evidence thus puts greater emphasis on confirmation methods, and clearly defines the distinction between the screened candidates and confirmed plastics. The identification technique used determines the size threshold that can be achieved, the throughput, and the kind of output data (particle-resolved or bulk polymer mass), which also implies exposure assessment and fate model implications[37].

3.4.1. Spectroscopy-Based Particle Identification (Micro-FTIR and Raman)

Micro FTIR and FTIR imaging have become relatively popular due to their ability to give spectral fingerprints of polymer specifics and may be applied with automated mapping to increase throughput. The extent to which Raman microscopy can be used to obtain smaller particle sizes is complementary to the extent to which fluorescence can be used, particularly with weathered particles and those covered with soil remnants or biofilms. The two approaches should both have the careful spectral matching standards, a known library, as well as an explicit report on how the ambiguous spectra were dealt with. Pretreatment quality in the soils has a strong influence on the spectral success, and hence, the rates of identification ought to be reported together with the extraction and digestion conditions. To provide overall synthesis, it is also significant to note that the methods can under-represent the small size fractions when the smallest detectable size is greater than the actual environmental size, which will lead to biases in the distribution of sizes inferred as well as the estimation of exposure[54].

3.4.2. Thermal Methods: Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS), Thermal Extraction/Desorption-Gas Chromatography/Mass Spectrometry (TED-GC/MS)

Thermal techniques measure the mass of polymers by decomposing samples and characterizing the products of the degradation. They can be used in complex matrices when counting the particles is infeasible, and they are also used in bulk mass budgets when modeling transport and performing risk assessment. Additives or polymer blends can also be identified using thermal methods, provided that the methods are sufficiently resolved. Nevertheless, they do not keep the particle-level data: size, shape, and color, which can largely be significant predictors of ingestion probability and physical impacts in soil organisms. Thermal analysis may prove to be the most informative in full characterization when used together with spectroscopy; particle metrics can be correlated with polymer mass, and cross-study comparability can be enhanced across various reporting units[55,56].

3.4.3. Visual Sorting and Staining: Role and Limitations

Screening, Visual sorting, and staining may be very fast, but their usefulness is constrained by false positives and operator bias. Natural cellulose fibers, keratin fibers, and fragments of organic matter may mimic plastic fibers and fragments, and staining may adsorb non-plastic materials, based on protocol and sample composition. In the case of SCI-standard synthesis, these methods are supposed to be placed as pre-steps that must be followed by confirmatory spectroscopy or thermal analysis to ascertain the presence of the polymers. In studies where visual classification has been involved, the results should be approached with caution, especially when abundances of the results are close to blank levels or where the dominance of fibers may be the manifestation of contamination[57,58]. A comparative overview of the main analytical approaches used for terrestrial microplastic detection and characterization is provided in **Table 2**.

Table 2. Overview of detection and characterization methods for terrestrial microplastics.

Method Family	Typical Terrestrial Application	Practical Size Window (Approx.)	Primary Output	Polymer Confirmation	Strengths in Soils	Key Limitations/Biases
Visual microscopy (stereo/light)	Screening of candidate particles after extraction	>300–500 µm	Counts, morphology, color	No (unless paired)	Fast screening, low cost	High false positives (natural fibers/organic debris), operator bias; not definitive
Fluorescent staining (e.g., Nile Red) + microscopy	Rapid screening of suspected MPs on filters	~20–300 µm (matrix-dependent)	Counts (fluorescent "MP-like")	No (unless paired)	Enhances contrast for weathered/dirty particles	Stains some non-plastics; needs confirmatory identification (ID); fluorescence varies by polymer/aging
micro-Fourier-transform infrared spectroscopy (micro-FTIR or µFTIR)/FTIR imaging	Routine particle-by-particle or mapped identification	~10–20 µm to mm	Counts + polymer type + size/shape	Yes	Widely accepted confirmatory method; good libraries	Throughput constraints; organic residues/clays interfere; lower size limit affects comparability
Raman microscopy	Confirmatory ID, often for smaller particles	~1–10 µm to mm	Counts + polymer type + size/shape	Yes	Higher spatial resolution than FTIR	Fluorescence interference common in soils; careful cleaning needed; slower for large n
Py-GC/MS	Bulk polymer mass in soil or fine fractions	Not size-resolved	Polymer mass (mg/kg)	Yes (mass signatures)	Works with complex matrices; supports mass balance	Loses particle metrics (size/shape/count); method development needed for complex mixtures
TED-GC/MS (thermal extraction/desorption)	Bulk polymer mass; sometimes additive signals	Not size-resolved	Polymer mass; select additives	Yes (mass signatures)	Higher throughput than particle-by-particle	Same loss of particle metrics; interpretation depends on calibration and target analytes
scanning electron microscopy/energy-dispersive spectroscopy (SEM/EDS) (with spectroscopy pairing)	Morphology and surface features; support for aging/particle type	Typically >1 µm	Morphology, elemental signals	No for polymers	Reveals weathering, biofilms, mineral attachment	Does not confirm polymer identity alone; costly; not quantitative by itself
Automated imaging + Machine Learning (ML) (paired with FTIR/Raman)	High-throughput particle detection/ classification	Depends on imaging + confirmatory method	Counts + morphology; verified polymer	Yes (if paired)	Reduces operator bias; boosts throughput	Requires strong validation; false positives without spectroscopy; training set dependence

3.5. Quantification: Metrics, Units, and Comparability

The interpretability of terrestrial MP data is dependent on quantification decisions made on data across sites and land uses, and studies. Ingestion exposure can be of most interest in particle-based metrics, whereas material flow analysis and transport modeling can be more directly associated with mass-based metrics. The non-harmonized nature of reporting has obstructed synthesis due to the variation in the size ranges covered by studies (which may be blank-corrected and recovery-adjusted or not). Extensive reviews should thus focus on uniform units as well as clarity of documentation of the analysis window[59].

3.5.1. Particle-Based vs. Mass-Based Reporting

The abundance of the particles is often measured in the number of particles in kilograms of dry soil, whereas the surface deposition research could record the amount of particles in every square meter. Mass concentrations are usually given in milligrams of polymer per kilogram of dry soil. Counts of particles give a measure of the rates of contact, and are sensitive to the behaviors of fragmentation, but mass measures give the loads of polymer and could be more indicative of long-term accumulation rates and export rates. The fact that fragmentation can make counts higher without making mass higher can mean different risk stories when used alone, as they can suggest. Extensive reporting and synthesis, thus, have the advantage of reporting the two metrics where possible and explicitly identifying the range of particle size and the confidence of identification with each[60].

3.5.2. Size Range and Detection Limit Transparency

The minimum size of the detected object is the most frequently used and most critical determinant of reported abundance. Even in similar conditions, studies that examine down to tens of micrometers frequently have significantly more particles than those constrained to hundreds of micrometers, even when similar conditions are used. Hence, each dataset should be viewed in terms of its operation size window. Explicit reports of minimum and maximum particle size, size-bin definitions, and the method of approach to measurement should be regarded as indispensable in reviews. In case nano plastics were not the focus, this limitation cannot be expressed artfully, as it restricts the conclusions on mobility, bioavailability, and internalization possibilities[61].

3.5.3. Morphology and Polymer Descriptors

In addition to abundance, shape and polymer identity characterization are vital to making inferences on a source and ecotoxicology. Fibers, films, and fragments vary in their behavior during transport, their ingestion probability, and polymer type vary in terms of density, ageing, and additive composition. Full datasets must consequently record morphology distributions and the type of polymers with confirmation rates. The interpretation of the source can be assisted by color and qualitative weathering indicators, but such descriptors are only intended to support rather than determine the source, particularly in situations where the appearance may be biased by contamination or sample handling[62].

3.6. Reference Materials, Method Validation, and Interlaboratory Harmonization

Advancements in the reliable synthesis and risk assessment of soil are limited by the poor standardization of reference materials and validation procedures of soil matrices. The use of method validation needs reference particles representative of real polymers, morphologies, and size regimes, and capable of universal use across laboratories. Since efficiencies of extraction can change radically depending on the soil type, validation must have representative soils or at least give a report on the soil properties, allowing inference about performance. Interlaboratory comparisons must be used to determine systematic biases that are introduced by the choice of digestion, density separation parameters, filtration steps, and spectral matching thresholds. Harmonization is not limited to methods but should also cover reporting templates that record minimum metadata in order to be able to do meta-analyses to consider size windows, recoveries, and blank levels, rather than to consider all reported concentrations as comparable[63].

3.7. Emerging Approaches and Frontier Challenges

3.7.1. Nanoplastics Detection in Soils

It has been widely postulated that nano plastics themselves could be more mobile and possibly more bioavailable than large particles, although the measurement can be constrained by low concentrations, high background, and the inability to prove the presence of a polymer at the nanoscale, as well as confirming its identity. Current approaches are frequently based on an operational definition using fractionation or filtration, or on results from indirect chemical signatures. These can be informative, but are not always directly comparable to studies. In-depth synthesis must thus consider the nano plastics findings with due care to the dependence on methods, and also emphasize the urgency of the validated workflows to integrate size fractionation with strong polymer confirmation[64].

3.7.2. Automated Imaging and Machine Learning

In greater measure, automated particle detection with spectral verification is applied to enhance the throughput and decrease subjectivity. Machine learning may be used to assist in particle segmentation, morphology classification, and prioritizing candidate particles to undergo confirmatory analysis and the success of this depends on training data quality, validation metric transparency, and reliable processing of ambiguous particles. Speed alone should not be used as a reason to not consider automated methods in review synthesis, as one can also determine the error structure, such as false positives in fiber-laden samples and false negatives of weathered or biofilm-coated particles[65].

3.7.3. Chemical "Fingerprinting" for Source Apportionment

The new focus of the source apportionment is shifting away from polymer type to chemical fingerprints, which are based upon additive profiles and co-occurring tracers. Signatures of road-related particles or types of products can be obtained by thermal techniques and specific chemical analysis, and these can be used together with land-use data to enhance causal inference of dominant sources. With age, however, mixing of different sources and additive loss may cause the blurring of fingerprints over time, and this means that extensive interpretation requires scrupulous association of chemical signals to likely source routes and environmental histories.

The boundary of evidentiary treatment of all further assertions regarding transport, exposure, and ecological risk is detected and characterized. In the case of terrestrial microplastics, the strongest research is that which clearly outlines the area of sampling, uses stringent contamination measures, counts recoveries and detection limits, and uses confirmatory polymer identification using clear criteria. A thorough synthesis of the literature requires uniform reporting of size windows, morphology distributions, polymer confirmation rates, and dealing with blanks and recoveries. Setting and embracing minimum reporting standards, based on certified reference materials and interlaboratory comparisons, is thus a prerequisite step to transforming the fast-growing mass of measurements into similar evidence potentially useful in modeling, risk assessment, and management decisions [66–69].

Practically, the strong design of the identification and characterization of terrestrial microplastics needs a fit-to-purpose analysis plan in line with the study aims and ranges of target sizes. It is important that the researchers state the intended purpose (counts, size, morphology, polymer type) and whether it is particle-resolved characterization or bulk polymer mass quantification (e.g., spectroscopic imaging or thermal analysis is the method of choice). The factors that are important to improve the credibility of data and cross-study comparability are strict control of contamination, inclusion of procedure and field blanks, recovery tests, and clear reporting of size detection limits and identification criteria. Polymer confirmation by spectroscopic methods should be used to reduce the use of false positives whenever possible in visual or fluorescence-based screening. Since matrix effects of soils are high, there should be a set of protocols to be followed during extraction procedures that are verified and clustered to distinct soils. Lastly, a uniform reporting of size classes, concentration units (particles kg^{-1} and/or mg kg^{-1}), and quality assurance measures should be given priority so that the methodological heterogeneity can be minimized and can enhance the exposure and risk interpretation [70].

4. Sources and Transport Pathways

Microplastics (MPs) find their way into terrestrial ecosystems as a result of an amalgamation of point sources, diffuse emissions, and redistribution of already polluted stocks. The soils in the majority of the landscapes can act as both a receiving and a long-term storage, as well as export MPs to fresh water systems or the atmosphere through erosion and resuspension. Knowledge of sources and pathways following this must be associated (i) with the predominant input vectors which fix particle type and loading rate, (ii) with the soil processes which regulate retention vs. mobilization, and (iii) with the landscape connectivity which rules offsite transport. This part summarizes the key sources of terrestrial MP and the significant physical, chemical, and biological processes that contribute to the movement of matter between and within compartments of the Earth [71].

4.1. Major Sources of Microplastics to Terrestrial Ecosystems

4.1.1. Agricultural Plastics and On-Farm Activities

Agriculture is often cited as a significant source of MP loads to the land due to the systematic application of plastics in the fields and then breaking them down due to Ultraviolet (UV) exposure, temperature variations, and mechanical forces. Large amounts of films and fragments can be produced during the process of weathering and abrasion by soil particles and farm machinery used to mulch films, greenhouse covers, silage wraps, irrigation components, and protective nets. And despite the retrieval and the disposal, partial removal, tearing, and integration into soil in the process of tillage may result in a portion of plastic remaining, which later breaks up as time goes by. Film-like morphologies and low-density polymers tend to dominate the resulting particles; however, composition is different depending on local practice and product selection. Notably, these inputs are not unique but recurring seasonally, with accumulation of the chronic as well as episodic pulses of fragments in the course of installation, maintenance, and removal[72].

The comparative significance of land-based sources of microplastics seems to be very land-use-based. Plastic mulching, as well as the use of biosolids, are some of the most well-known examples of direct inputs in intensively managed agricultural systems, which have been substantiated by a number of field measurements. Located masses Road traffic-generated particles and litter fragmentation are probably the biggest contributors to localized loading, but have not been quantitatively apportioned. The atmospheric deposition can be the main input in remote or forested areas, as per the developing monitoring research, but the flux estimates differ extensively in the climatic zones[73].

4.1.2. Organic Amendments, Biosolids, Compost, and Manure

A second major pathway is land application of organic amendment material, such as composted municipal waste and manure, sewage sludge/biosolids. These wastes may include large quantities of fibers and fragments of consumer packaging, fabrics, and dissolved plastics washed through waste sorting and wastewater treatment. When deposited on the ground, they offer a direct way of spreading MPs over agricultural land, typically in a more or less homogeneous way at field size as compared to local litter sources. Since amendments can also change the soil structure, microbial activity, and the contents of organic matter, they can affect not only MP inputs but also the later transport and bioavailability. In the case of risk-oriented synthesis, this pathway is particularly important considering the potential coupling of MP loading to MP co-occurring chemicals (nutrients, metals, pharmaceuticals) and changes in soil biogeochemistry, which may affect fate and effects[74].

4.1.3. Urban, Industrial, and Construction-Related Sources

The urban landscapes are sources of MPs litter fragmentation, building materials, construction debris, synthetic turf infill, and emissions relating to plastic goods. Heterogeneous mixtures of fragments and fibers caused by these sources tend to reach high levels in space around high foot traffic, storm drains, construction areas, and waste processing centers. The urban sources are often more polymer diverse than agricultural plastics, which are often polymer specific and morphology specific (e.g., films), and may also have pigmented or composite materials that are difficult to identify. The urban soils and green areas may hence become reservoirs that are recharged again and again by deposition and disturbed by the maintenance activities, becoming more susceptible to resuspension and export as a result of runoffs[75].

4.1.4. Road Traffic and Road-Associated Particles

Another category of source that is unique and, in most cases, predominant in most areas is road environments, which is a result of tire wear, brake wear, road-marking abrasion, and the breaking of roadside litter. These particles may be deposited onto the neighboring soils directly and may also be carried through stormwater, road ditch systems, and even the wind. Particles related to roads do not necessarily have the same composition and density as more traditional microplastics and are often co-mingled with mineral dust, soot, and metals, resulting in complex mixtures with potentially alternative transport behavior and toxicological characteristics than pure polymer fragments. Their value is not only in their mass loading along traffic corridors but also in their effective some sort of coupling to the hydrological transport in case of rainfall events[76].

4.1.5. Atmospheric Deposition and Long-Range Transport

Microplastics have now become pervasive in the atmosphere as fibers and small fragments and can be deposited on terrestrial surfaces at great distances from the sources. Atmospheric deposition also adds to the contamination of the diffuse background and may be particularly significant in remote soils, where the local use of plastics is not very active. On the other hand, soils can be the secondary sources to the atmosphere in cases where the surface particles are resuspended due to dry and windy conditions or due to agricultural activities. This mutual exchange will form a dynamic soil-air cycle that will be able to redistribute MPs on landscapes and make it difficult to assign sources on the basis of their proximity to visible local sources alone[77]. The dominant terrestrial sources of microplastics and their typical particle signatures are summarized in **Table 3**.

Table 3. Major terrestrial sources of microplastics and their characteristic signatures.

Source Category	Dominant Morphologies	Common Polymer Patterns (Typical)	Likely Receiving Environments/Hotspots	Notes for Source Inference
Agricultural plastic use (mulch, greenhouse, silage, nets)	Films, fragments	polyethylene (PE), polypropylene (PP) (often)	Plastic-mulched fields; greenhouse soils; field edges; tillage zones	Seasonal pulses; fragmentation accelerates with UV + mechanical abrasion
Compost and municipal organic amendments	Fibers, fragments	Mixed polymers; frequent textile-related materials	Horticultural soils; amended cropland	Reflects upstream waste sorting quality; often co-delivered with organic matter
Biosolids/sewage sludge application	Fibers, fragments; fine particles	Mixed polymers; treatment-dependent	Sludge-amended agricultural soils	Strong pathway for broad regional loading; often coupled with nutrient inputs
Manure (livestock feed packaging, barn plastics)	Fibers, fragments	Mixed; farm-material dependent	Pastures; manure-applied fields	Can co-occur with bedding-derived fibers; varies by farm management
Urban litter fragmentation	Fragments, foams, films	Diverse (packaging-dominated)	Urban greenspaces; vacant lots; storm drain inlets	Hotspot-driven; influenced by cleanup frequency and land maintenance
Construction and demolition activity	Fragments, chips, composites	Diverse; may include coated/composite materials	Construction sites; roadside soils near projects	Can include non-standard materials (composites) complicating identification
Road traffic (tire/road wear, markings)	Irregular particles; mixed with mineral dust	Complex mixtures; "traffic-derived" signatures	Road verges, ditches, stormwater sediments	Often co-occurs with metals/soot; strong storm-event transport to drains
Atmospheric deposition (local + long-range)	Fibers; small fragments	Often fiber-rich, mixed polymers	Remote soils; mountain/forest catchments; rooftops/dry deposition collectors	Can obscure local signals; requires deposition monitoring for attribution

4.2. Transport Processes within Soils

4.2.1. Retention, Aggregation, and Soil Microstructure

In the soil, the MPs react with aggregates, organic matter, and mineral surfaces. Retention is commonly improved on the condition that particles are physically trapped in aggregates or covered by organic components and biofilms and thereby enhancing effective density and incorporation into soil structure. The fine particles may be incorporated into microaggregates, where they are not subject to physical removal, although they may not be inaccessible to microfauna and microbes. On the other hand, soils that have low aggregation or disturbance can retain MPs less efficiently, and thus, they get redistributed by way of percolation and erosion. Since these processes do not change the quantity of particles on scales larger than those of aggregates and pores, the bulk concentration can be very different in exposure landscapes for soil organisms, depending on the distribution of particles between microhabitats [78,79].

4.2.2. Vertical Transport by Biota, Roots, and Preferential Flow

The process of vertical redistribution is supported by biological and physical processes. Transport of particles downwards by ingestion, casting and burrowing, and mixing of soil can be done by bioturbation by earthworms and other soil engineers. Macropores and preferential pathways may form around roots and within the soil, which may aid smaller particles to move downwards as part of the infiltration. Shrink–swell cycles, cracking, and freeze–thaw dynamics can also support vertical movement in the form of opening any partial, temporary pathways and pulling the particle redistribution by changes in soil structure. The overall effect of this is a depth profile which is indicative not only of surface inputs, but of the interaction between the biological activity, soil structure, and hydrological regime, and smaller grains tending to penetrate further in one which prefers preferential transport [80].

4.2.3. Lateral Transport by Runoff, Erosion, and Tillage

Surface runoff and erosion usually dominate as the lateral movement, particularly when the rainfall or the landscape is sloped. Microplastics may be eroded to be carried with the soil particles, entrenched in organic debris, or carried as free particles based on size, density, and surface characteristics. Agricultural practices have a potentially strong impact on these fluxes; tillage practices can incorporate plastics into soil (offering reduced immediate surface availability) but can also break up aggregation and increase the susceptibility to erosion, whereas conservation practices can reduce soil losses and consequently reduce MP export but, where inputs continue, may also allow for increased near-surface retention. Plastics can also be transported in a field through tillage and field operations and can be concentrated along the boundaries, wheel tracks, and areas of deposition. The addition of impervious surfaces in cities and the engineered drainage quickly attaches the deposited particles to the stormwater inundations, transporting MPs to the surrounding soils and waterways in pulsatile inundations[81].

4.2.4. Wind-Driven Resuspension and Aeolian Transport

The wind will be able to move fine soil particles and other MPs that reside on dry surfaces, especially in bare fields, construction works, and road edges. The aerodynamic characteristics and low settling velocities of fibers and small fragments might result in their preferential resolution, leading to a redistribution route over both local and regional scales. Aeolian processes are intermittent and are highly influenced by surface moisture, the vegetation cover, soil crusts, and the intensity of disturbance. Since resuspension is also a producer of human exposure pathways (dust inhalation and ingestion), it is a point of intersection between environmental fate and population health, despite the fact that the main concern has to be ecological risk[82].

The most effective process of lateral transport is hydrologically driven by run-off and erosion in areas with high rainfall intensity, slopes and low vegetation cover. On the other hand, resuspension via the wind and redistribution by dust can become relatively more significant in arid and semi-arid areas, but have not been empirically quantified due to their relatively minor contributions. Vertical redistribution by bioturbation and preferential flow is always found across soil types but normally on a local scale, not landscape scale[83].

4.3. Physicochemical Controls on Mobility and Partitioning

4.3.1. Particle Properties: Size, Shape, Density, and Surface Condition

The mobility is usually increased as the particle size decreases, although shape can also play an equal role. Entrapment of fibers may be by entrapment by roots and organic material, or can be transported effectively when they travel along the course of flow, and films may be folded and act randomly when they are in pore networks. The density controls the flotation and sedimentation in water flows and defines separation in soil pore water in infiltration and runoff. The surfaces become aged and grow biofilms that change the hydrophobicity and surface charge, and roughness, which affect the aggregation, sorption, and attachment of the mineral. Such shifting properties imply that polymer identity cannot on its own be trusted as valuable in inferences on transport: the same polymer would behave differently depending on whether it is transported weathered or coated with biofilm[82].

4.3.2. Soil Properties: Texture, Organic Matter, Moisture, and Chemistry

The soil texture influences the distribution of pore size and hence the thresholds of particle movement. Larger pores in coarse soils can be more permeable to the penetration of small MPs, whilst fine-textured soils can entrap the particles by filtration and an intense process of aggregation, though they can be transported through cracks and macropores. Organic material is capable of increasing retention through promoting aggregation and coating particles, but may increase ingestion by detritivores when particles obtain organic-rich eco-coronas. The moisture regime influences the hydrological transport and resuspension of the surfaces: in wet conditions, runoff and percolation are prevalent, whereas in dry conditions, wind mobilization is prevalent. The soil chemistry, such as ionic strength and pH, affects electrostatic interactions that may facilitate adherence or dispersal to affect the movement of MPs as individual particles or as flocs[9,84].

The only particle-level control that seems to be well supported in findings, in one or another study, is size, with smaller particles demonstrating higher potential to transport vertically and laterally. Data on the effects of polymer density in soils is less reliable than in aquatic environments, indicating that buoyancy effects can be counteracted by the action of matrices in most terrestrial environments[85]. Important transport pathways and their controlling factors across terrestrial compartments are synthesized in **Table 4**. The main within- and between-compartment transport pathways (soil-air, soil-water, vertical mixing, and lateral redistribution) are summarized in **Figure 3**.

Table 4. Transport pathways and controlling factors in terrestrial ecosystems.

Pathway Type	Mechanism (How MPs Move)	Dominant Scale	Main Environmental Drivers	Particle Traits That Matter Most	Common Evidence/Metrics Used	Management Levers
Vertical transport	Bioturbation, root channels, preferential flow, cracking/freeze–thaw	Profile (cm–m)	Soil structure, moisture regime, soil fauna activity	Smaller size; flexible fibers; aged surfaces	Depth profiles; biota casts; pore-water/leachate sampling	Reduce inputs; manage tillage; maintain soil structure; limit preferential-flow mobilization where feasible
Lateral transport on land	Runoff and erosion; sediment attachment; field redistribution by operations	Field–catchment	Rain intensity, slope, vegetation cover, soil erodibility	Density, size, attachment to soil/organic matter	Runoff plots; sediment loads; storm-event sampling	Erosion control (cover crops, buffers); runoff retention; slope management
Soil–water export	Drainage/tile flow; stream entry via overland flow; floodplain deposition	Catchment–river network	Hydrologic connectivity, storm events, drainage infrastructure	Fine fraction; buoyancy in flow; flocculation tendency	Event-based flux; stream sediments; drainage effluent	Stormwater controls; retention basins; sediment traps; riparian buffers
Soil–air exchange	Resuspension of dust-bound MPs; deposition from air	Local–regional	Wind, soil dryness, disturbance (tillage/traffic)	Fibers, small fragments; low settling velocity	Dust collectors; deposition gauges; near-road gradients	Surface cover/vegetation; dust suppression; reduced disturbance; roadside sediment management
Within-soil retention	Aggregate entrapment; organic/mineral coating; biofilm-induced flocculation	Microhabitat	Organic matter, aggregation dynamics, microbial activity	Surface aging; roughness; eco-corona	Fractionation into aggregates; microscopy of aggregate interiors	Improve soil stability; reduce disturbance; prevent new inputs (retention can mean long-term exposure)
Biological transfer	Ingestion/egestion; prey-mediated movement; animal movement across habitats	Microhabitat–landscape	Food web structure, organism behavior, habitat connectivity	Size and shape affecting ingestion/retention	Gut content; egesta; trophic studies	Reduce exposure at hotspots; manage inputs where key receptors dominate

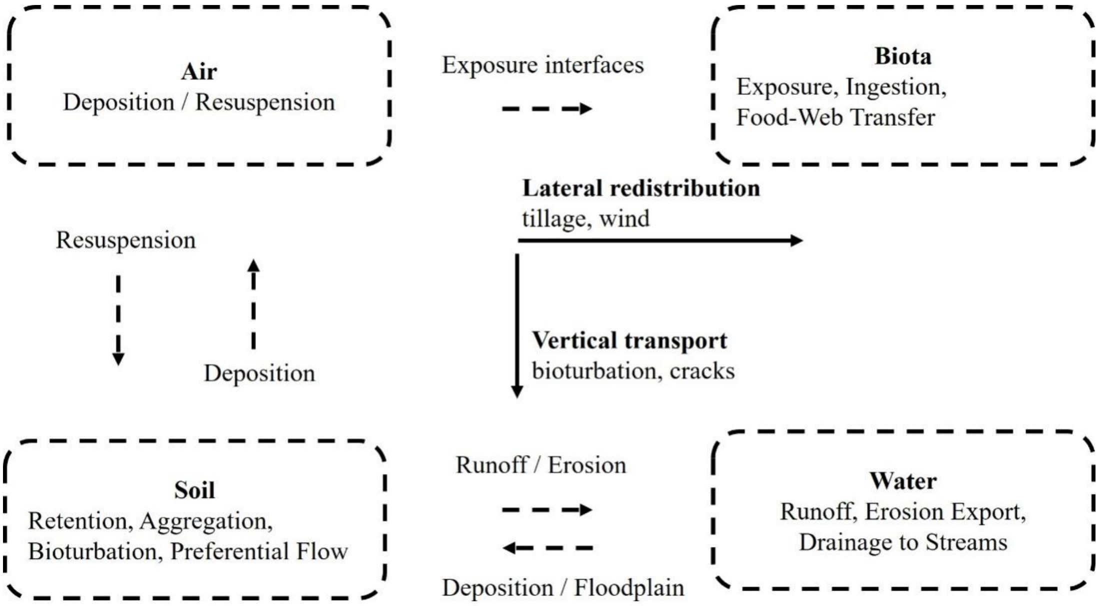

Figure 3. Transport pathways within and between compartments.

4.4. Transformation and Aging along Transport Pathways

4.4.1. Fragmentation and Weathering in Terrestrial Settings

Mechanical abrasion, cyclic temperature, and surface oxidation using photo-oxidation all cause the fragments of plastics to continue breaking down in soils where particles are left exposed. Fragmentation elevates the number of particles and moves the distributions to smaller sizes that may enhance mobility and modify bioavailability. Also, weathered particles acquire cracks and surface functional groups, which vary sorption behavior and mineral and microbial interactions. Since transport and toxicity tend to vary with the size and condition of surfaces, transformation is not only a background process but a cause of shifting hazard and exposure profiles across time[86].

4.4.2. Biofilm Formation and Eco-Corona Development

Microplastics quickly become coated with organic materials and microbial biofilms in soils. These coatings are able to enhance effective density, enhance aggregation, and alter the recognition and ingestion of the particles by the soil fauna. There is also the potential of biofilms to modify chemical exchange processes, such as additive leaching and sorption of co-contaminants, through the incorporation of reactive functional groups and the modulation of diffusion barriers. Pathway-wise, eco-coronas have the potential to transform the plastic-like surfaces into soil-like particles, which have the potential to enhance retention in aggregates and also enhance biological interaction.

4.4.3. Chemical Release and Interactions with Co-Contaminants

Additives can leech out of the plastic and external pollutants can adsorb onto the plastic as they age. These exchanges are dependent on the direction and magnitude with respect to soil organic carbon, contaminant characteristics, and the extent of aging of the particle. These interactions can be changed by transport processes that cycle particles in and out of toxic and anoxic macrozones, wet and dry phases, and various organic matter environments, and generate time-dependent changes in contaminant partitioning. On the part of terrestrial risk assessment, this means that the chemical aspect of microplastic transportation is dynamic and context-specific and not a constant attribute of the polymer[87].

4.5. Connectivity across Compartments and Landscape-Scale Export

4.5.1. Soil–Water Coupling and Fluvial Export

One of the main landscape export mechanisms is the soil to the stream movement through overland flow, tile drainage, and soil erosion. MPs can either be carried along in runoff as free particles or incorporated within organic matter or attached to mobilizing sediments, and their export can also be event-based, where storms can disproportionately contribute to the export. Particles in the waters can be held within riparian areas and sediments, moved downstream, or re-allocated onto floodplains with inundation, forming feedback processes of land and water areas[88].

4.5.2. Soil–Air Exchange and Regional Redistribution

Soil surfaces may be exposed to atmospheric deposition of MPs and also release MPs through resuspension, particularly in disturbed or dry soils. This trade may distribute pollution across land-use borders and form diffuse backgrounds even in places that do not have any apparent sources. It further complicates the attempts to pinpoint soil pollution to local management practices only, since atmospheric inputs may obscure or exaggerate local indications.

4.5.3. Plant-Mediated Movement and Food-Web Transfer

Plants can also have an indirect effect on MP distribution by changing soil structure through root penetration, erosion resistance, and microbial rhizosphere organization. Direct internalization and translocation are a controversial process and where found seem most likely in very small particles; in any case, plant surfaces and rhizosphere areas are the exposures that herbivores and decomposers are exposed to. The transfer of MPs across trophic levels through food-webs may be important, particularly when prey retain particles in the gut, but retention and accumulation patterns are highly species- and particle-specific. Transport-wise, food webs are biological pathways, which may facilitate the movement of particles across microhabitats and in certain instances through animal movements across ecosystem boundaries[89].

4.6. Implications for Modeling and Source Attribution

Transport knowledge is becoming more dependent upon making empirical measurements with models reflecting accumulation, mobilization, and export. The conceptual representation of soils as reservoirs under the mass-balance frameworks may have its sources of input through various sources and output via erosion, runoff, leaching, and resuspension. Yet, a solid parameterization entails a regular set of information on size distributions, polymer identity, and retention/mobilization rate in various soils and climatic conditions. The advantages of source attribution are that it combines the polymer profile as well as the morphology profile with land-use and proximity data, yet it is nonetheless complicated by the aging, mixing, and redistribution of sources. Converging evidence, i.e., particle properties that are consistent with a possible source, gradient of spatial distributions that are consistent with source location, and transport pathways that are backed up by hydro/atmospheric measurements, tends to give the most powerful inferences[90].

The source terrestrial microplastics have a wide array of sources, and agriculture, organic amendments, urban processes, road traffic, and atmospheric deposition are often the major contributors based on the scene conditions. Their further transport is dictated by the interaction of soil structure, hydrology, biological mixing, and particle characteristics that develop in the form of weathering and biofilm. The soils serve as a source as well as sinks, whereby they may export particles to the waterways and the atmosphere, especially during an episodic event like a storm. These sources and pathways are a subject that needs a thorough comprehension to help understand the spatial patterns of field datasets, to design ecotoxicological exposure scenarios that are realistic, and to set priorities on the most influential inputs or transport pathways on the way to prioritizing mitigation strategies[91].

5. Management, Mitigation, and Future Directions

To manage microplastics (MPs) in the terrestrial environment, it is necessary to transition to measuring what is already present to actively reducing inputs, reducing redistribution, and creating evidence frameworks that can be used to support regulation, as well as the practical implementation of decisions. Compared to most point-source pollutants, terrestrial MPs are a result of a diverse suite of diffuse sources, and they are physically fixed in soils. Once established, they are hard to get out of. In turn, the most justifiable approach is the prevention-first: determining the prevailing source groups in a specified landscape, mitigating the source of emissions, interrupting transport corridors (runoff, erosion, stormwater, and resuspension), and installing monitoring mechanisms to confirm progress in time. This part is used to synthesize management and mitigation options throughout the intervention chain and to state future research and standardization priorities required to translate the scientific knowledge into quantifiable risk mitigation[92].

A conceptual summary of how particle traits and soil/landscape properties jointly regulate retention versus mobilization is provided in **Figure 4**. In this case, it may be clear that the reduction of upstream sources in agricultural plastics and biosolid management is the potential source that provides the most significant mitigation leverage in densely populated agricultural areas. Conversely, stormwater and roadside sediment controls can be used to counter larger traffic-based inputs in urban surroundings. Nonetheless, management prioritization, because of a lack of quantitative source apportionment in most areas, is somewhat inductive and needs to be enhanced by using better monitoring[93].

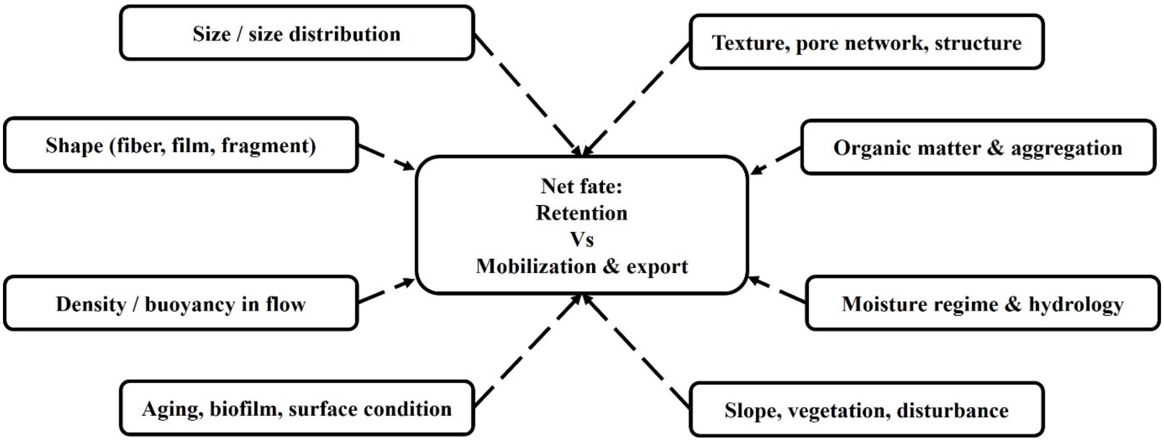

Figure 4. Controls on mobility and retention in soils.

5.1. Monitoring Frameworks and Standardization as Enabling Infrastructure

Without scientifically realistic and operationally realistic monitoring designs, it is impossible to evaluate management actions. In the case of terrestrial MPs, the harmonization of sampling depth, size window, polymer confirmation requirements, and reporting metrics such that time changes can be viewed as real trends and not artifacts of methodology will be very important. Monitoring frameworks are to be risk- and pathway-informed, so they must focus on compartments representative of both accumulations and export (e.g., top-soil in high-input land uses, roadside verges and drainage systems, riparian buffers, depositional zone, and runoff pathways and connected sediments). The importance of longitudinal monitoring is particularly due to the seasonality of many agricultural and urban inputs, and since soils are long-term reservoirs, a short time of study will fail to capture episodic export due to storms or disturbances that prevail in annual fluxes.

Comparability across jurisdictions as well as projects is also supported by standardization. Minimum QA/QC requirements, such as blanks in the field and procedural blanks, corrections for recovery, and the explicit reporting of detection limits and size limits, are crucial for credibility. In situations where possible, the combination of particle-based metrics and polymer-mass metrics enhances both the ease with which monitoring outcomes can be related to mass-balance models and the extent to which interventions can be seen not only to change the number of particles (which can respond rapidly to fragmentation processes) but also the loads of polymer (which can better represent long-term accumulation). Finally, standardized monitoring is a kind of enabling infrastructure: it is not the end goal, up to which mitigation claims can be verified[94,95].

5.2. Source Reduction as the Highest-Leverage Mitigation Strategy

Since remediation in soil is hardly ever viable on a large scale, the most effective and cost-efficient remediation pathway to long-term risk reduction is source reduction. The interventions concerning intentional and inadvertent introduction of plastics into agricultural systems should be focused on both. Better design and management of agricultural films, nets, and irrigation parts can minimize their fragmentation during usage and during the rebreaking. It is how it is run as much as what it is replaced with; minimized tearing by proper installation and removal, intensive re-retrieval programs can help a lot in reducing the amount of waste plastic that remains to fragment in the soil. Where biodegradable or compostable alternatives are suggested, their deployment should be linked to field-based evidence of degradation under realistic soil conditions, attention being given to by-products and the potential for persistent microplastic residues if decomposition is incomplete[96].

Some of the source reduction methods in urban settings entail the use of better waste management to minimize litter fragmentation, management of construction and demolition wastes, and specific measures for high-emission activities. Textile fiber emissions constitute a significant diffusive route; one of the mitigation strategies includes upstream design options (reduced shedding of fibers), laundering and filtration methods, and better capturing in wastewater streams. Emissions from roads are more complicated due to the fact that they are linked to mobility, infrastructure, and mitigation is aimed at the generation reduction (material design, driving conditions), redistribution reduction (stormwater capture), and hotspot management (roadside sediment control). Notably, the prevailing sources change with the landscape and, therefore, the source reduction strategies should be prioritized locally, but not regarded as universal[97].

5.3. Controlling Transport Corridors through Land and Water Management

Runoff, erosion and the route of stormwater may remobilize previously deposited MPs even in scenarios where there is a reduction in inputs. Mitigation is, therefore, to incorporate measures that lower the connectivity of the soils contaminated and those receiving them. Soil erosion control measures to minimize soil loss, such as cover crops, residue retention, reduced disturbance, contour farming, and riparian buffers, will likely reduce MP export in agricultural landscapes, as MPs tend to be carried along mobilized soil and organic particles. Although the connection is not necessarily so direct, there is also a possibility of practices that minimize erosion, enhancing near-surface retention, in which exposure of surface-dwelling organisms could still exist. In line with this, interventions ought to be considered in terms of on-site retention and off-site export, and the monitoring designs must be oriented to each of these outcomes[98].

Stormwater systems in an urban setting are usually good conduits to transport the particles. Green infrastructure and engineered controls such as retention basins, sediment traps, constructed wetlands, and filtration systems can help reduce export to waterways and may also limit deposition onto adjacent soils during times of overflow. Especially relevant to roadside management, since particles related to roads are often concentrated in verges and drainage channels, maintenance activities that entail the removal and proper disposal of contaminated sediments can minimize downstream transport, but resuspension can be enhanced due to disturbance otherwise. The general aim is the reduction of the landscape connectivity on the transportation of particles, in particular events of high flow, which contribute disproportionately to annual exports[99].

5.4. Managing Organic Amendments, Biosolids, and Waste-Stream Pathways

The direct and non-negligible pathway of biosolids, compost, and manure land application as a source of microplastics to soils exists. The management options can thus stretch further out of the field practice into upstream waste and wastewater systems. Better removal in the wastewater treatment process, capture in the sludge processing procedure, and higher sorting and contamination reduction in compost feedstocks might decrease MP loads to the amendments. Nevertheless, disposal only transfers the material in the system of waste; it should be linked to proper handling, disposal, or treatment streams that do not reproduce MPs in other locations[100].

Risk-informed standards can be used where the use of biosolids and compost continues to be relevant to the objectives of soil fertility and the circular economy. These involve specifying quality criteria to be met on amendments in accordance with validated MP measures, establishing the allowable threshold of contamination by using standard techniques, and laying emphasis on application practices that reduce the redistribution (e.g., incorporation strategies weighted against erosion hazard). The fact that amendments are also sources of nutrients and other contaminants should be managed and not by MP-only, since it has been noted that MPs can interact with each other, with metals, organics, and microbial communities[100].

5.5. Remediation Feasibility and Realistic Endpoints

Microplastics are particulate and heterogeneous, unlike soluble contaminants, and are frequently deeply seated in the soil structure. Mass evacuation is hence limited by the practicability, price, and the danger of additional disruption. Localized hotspots like spill sites, industrial sites or highly contaminated roadside sediments are most likely to be remediated. Physical removal, soil replacement, or containment may be taken into consideration in such cases, but they should be evaluated with great consideration of the secondary effects, such as the disruption of habitats and the production of waste.

In the majority of agricultural and natural soils, control and stabilization, rather than eradication, should be the target of management, and aims at minimizing future inputs and transport to vulnerable receptors and downstream mechanisms. Realistic targets are thus not usually elimination, but quantifiable decreases in new loading rates, decreased export fluxes, and quantifiable decreases in exposure of key biological receptors with time. These terminals are more consistent with the manner in which particulate legacy pollutants are normally handled in soil[101].

5.6. Policy Translation and Stakeholder Implementation Considerations

Mitigation is based on whether interventions are aligned with the incentives of the stakeholders and changes in operations, which are feasible. The mitigation of agriculture should be done about the economics of the farm, the availability of substitute materials, as well as viable retrieval and disposal mechanisms. The city interventions need to be intercoordinated by the city services, stormwater management, and waste management systems. The transportation agencies and infrastructure planning are implicated in road-related mitigation. In both scenarios, the policy tools that can underpin the implementation process will be product standards that lessen fragmentation and shedding, extended producer responsibility schemes that enhance end-of-life management, quality norms of compost and biosolids, and stormwater rules that are aimed at controlling particulate contamination. Scientifically, it is not merely recording occurrence, but a method to standardize evidence that relates interventions to a reduced load and exposure that is of maximum value to policy[102].

5.7. Future Directions: Research Priorities That Enable Better Mitigation and Risk Reduction

A number of research requirements are especially consequential to the enhanced management outcomes. To begin with, method harmonization could proceed, interlaboratory validation, and reference materials that are specific to soils and typical terrestrial particle types, including fibers, films, and road-related particles, should be designed. Second, better knowledge of size-resolved fate and transport is needed to determine which fractions are most mobile and most biologically relevant in the field, such as the contribution of nano plastics, which is still insufficiently studied. Third, ecotoxicology needs to be more realistic in terms of exposures, aged particles, chronic endpoints, and co-stressor interactions that are more realistic of real soil situations, and to correlate the organism-level response to soil functions and ecosystem services. Fourth, the models that combine sources, retention, redistribution, and export with standardized monitoring data validation are required to determine where interventions will be most effective and work out efficient monitoring networks[103–105].

Last, mitigation studies, per se, will have to grow. Terrestrial MPs' intervention science is a relative infant; field testing the intervention practices, amendment standards, erosion control, and stormwater capture to deliver an evidence-based response to questions like what measurable MP outcomes are achievable is the first step to transform plausible strategies into evidence-based best practices. The low residence time of MPs in soils suggests that a slow rate of progress can still be realized; however, source reduction and pathway disruption can have significant payoffs in less future accumulation and less recovery to adjacent ecosystems[106,107].

6. Conclusions

The microplastics have become ubiquitous and intractable polluters of the terrestrial ecosystem, and soils have not only been the recipient of various plastic inputs but also reservoirs of these materials in the long term, which can subsequently serve as a secondary source to the freshwater system and the atmosphere. The evidence provided in this review suggests that anthropogenic microplastic loads are caused by a complex of deliberate uses of plastics in agricultural fields, diffuse urban and industrial emissions, road-traffic-related particles, atmospheric deposition, and land applications of organic amendments, including compost or biosolids. After introduction, the microplastics are recycled by interacting physical and biological processes, such as aggregation and retention in the soil structure, vertical mixing with bioturbation and preferential flow, and erosion and runoff lateral export. The pathways form very heterogeneous concentration fields of soils and landscapes that consequently define exposure environments of terrestrial organisms.

One conclusion is that the development of knowledge on the risks of microplastics on Earth is limited by both the variability of methodology and gaps in knowledge to the same extent. The soil is a very troublesome matrix, and variations in sampling depth, extraction efficiency, size detection limits, polymer confirmation techniques, contamination management, and reporting units may highly impact measured levels and inferred trends. Data sets of best quality are those that are backed with stringent QA/QC, clear blank, recovery correction, and verification of polymer identification via spectroscopic and/or thermal tests. Additional harmonization, particularly of minimum reporting standards and verified reference materials of soil matrices, is still necessary in order to facilitate effective cross-study comparisons, plausible meta-analyses, and parameterization of models.

The existing evidence indicates that soil invertebrates, plants, and microbial communities are widely exposed to microplastics, and laboratory studies show that both physical and chemical outcomes are plausible. In terrestrial environments, especially physical processes, such as gut filling and abrasion, and indirect processes, both of which are mediated by modulations of soil structure and microhabitats, are relevant. There are chemical aspects of risk in the additive release and interaction with co-contaminants depending on the context, but the direction and strength of effects are not always generalizable, and the effects are strongly influenced by the soil properties, particle aging state, and exposure conditions. Notably, there are numerous uncertainties in the translation of hazard data to field-relevant risk, especially because of poor modeling of environmentally relevant particle morphologies (fibers, films, and road-associated particles), lack of use of aged and biofilm-coated materials, and lack of chronic low-dose and multi-generational studies in realistic soil matrices. The conceptual and analytical distances are even greater when it comes to nanoplastics that might have different mobility and bioavailability, but cannot be easily detected and quantified as dependable in soils.

As a management issue, the environmentally based terrestrial microplastic issue possesses both high diffusiveness and high legacy, and therefore, mass-scale remediation is not feasible in the vast majority of environments. Therefore, the most promising interventions are preventive in nature and must focus on the reduction of the sources and preventing the pathway. Some of the most defensible strategies include agricultural patterns that reduce plastic waste and enhance recovery, stricter control of contamination in the compost and biosolids streams, stormwater and erosion controls, which reduce connectivity of transport. The success of such interventions is, however, reliant on frameworks of monitoring that are standardized, pathway-informed, and in a position to differentiate actual trends from methodological artifacts. Combining mass-based and particle-based indicators, concentrating on export-relevant compartments, and episodic transport events will turn out to be important in gauging practical effectiveness.

Finally, the existing evidence shows that in terrestrial ecosystems, microplastics management needs to be based primarily on strategies aimed at the interventions that result in the most regular input pathways. The recovery of plastic mulch films and their management, the discontinuation of the use of disposable agricultural plastics, and the use of durable or reusable alternatives are also some of the main mitigation priorities in agricultural systems. It is also important that biosolid use is further regulated and monitored, as the usage of wastewater-produced residues is reported to transfer microplastics to the soils. Urban settings have an opportunity to provide better management of stormwater and road runoff, such as sediment capturing and filtration, to lessen the redistribution of the traffic-related particles into the local soils. Just as significant is the growth of standard monitoring procedures as well as the increase in wastewater treatment processes in terms of their removal capabilities in restricting the volume of environmental release at the point of origin. All these combined explain that even in the face of scientific uncertainties, a combination of current evidence shows that a number of practical and precautionary measures can be identified that have the potential to substantially decrease the number of terrestrial microplastic contributions.

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Conflicts of Interest

The authors declare no conflict of interest.

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