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Microplastics-Induced Perturbations in Soil Agroecosystems: Ecological Risks and Sustainable Management Strategies

Joseph Ekenwosu[1]*, Ann Gunina[2]

[1]Department of Animal and Environmental Biology, Imo State University, Nigeria
[2]Department of Soil Biogeochemistry, OWL University of Applied Sciencesand Arts (TH OWL), Germany

*Correspondence: josephekenwosu@gmail.com

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ABSTRACT: Microplastics (MPs) are persistent particulate pollutants that accumulate in agricultural soils through plasticulture, waste-derived amendments, irrigation, atmospheric deposition, and the fragmentation of larger plastic materials. This review synthesises current evidence on their sources, input pathways, environmental fate, ecological impacts on soils, and implications for climate-smart agriculture, with particular emphasis on the factors influencing the direction and magnitude of their effects. Available evidence indicates that polymer type, particle size and shape, ageing, soil texture, hydrological conditions, bioturbation, and agricultural management practices collectively influence MP persistence and transport. Quantitative analyses have identified measurable changes in plant productivity, soil fertility, microbial diversity, carbon pools, soil respiration, and extracellular enzyme activities. However, the magnitude of these effects varies considerably depending on exposure concentrations, experimental conditions, and environmental characteristics. Recent field investigations further suggest that effects observed under laboratory conditions may not occur to the same extent in natural agricultural environments. Microplastics can modify soil physical properties and microbial habitats, potentially affecting carbon cycling and nitrogen transformations. Effective management strategies should therefore prioritise pollution prevention, responsible use and recovery of agricultural plastics, quality assurance of waste-derived amendments, site-specific soil and water management, standardised monitoring protocols, and evidence-based regulatory measures. Future research should focus on environmentally realistic field experiments, harmonised analytical methodologies, polymer-specific exposure assessments, long-term monitoring, and integrated evaluations of soil health to better understand the ecological consequences of MP contamination in agricultural systems.

KEYWORDS: Microplastics; agricultural soils; soil health; soil ecology; agroecosystem functions; climate-smart agriculture

1. Introduction

Plastics are extensively used in modern agricultural systems because of their durability, lightweight properties, versatility, and cost-effectiveness. Their applications include irrigation equipment, greenhouse coverings, mulch films, packaging materials, and polymer-coated agricultural inputs. However, the characteristics that make plastics valuable for agricultural production also contribute to their environmental persistence and accumulation following disposal or degradation. Consequently, agricultural soils have become important terrestrial reservoirs of plastic debris and microplastics (MPs) [1–3]. The widespread release of plastic materials has emerged as a major global environmental concern, affecting both terrestrial and aquatic ecosystems [4, 5].

Microplastics are generally defined as plastic particles smaller than 5 mm and are classified as primary MPs, which are manufactured or released directly as small particles, or secondary MPs, which originate from the fragmentation of larger plastic materials [2, 6]. Their environmental significance extends beyond their persistence, as they can modify soil physical characteristics, interact with organic and mineral constituents, influence microbial habitats, and facilitate interactions with other environmental contaminants [7–10]. Unlike aquatic environments, agricultural soils can retain particulate pollutants over extended periods. Continuous inputs from plasticulture, sewage sludge, compost, irrigation water, and atmospheric deposition, combined with the gradual fragmentation of existing plastic residues, produce complex mixtures of MPs with different polymer compositions, particle sizes, morphologies, and degrees of environmental ageing [11–21].

The major environmental problem associated with MP contamination in agricultural soils is its potential to disrupt essential soil functions that support agricultural productivity and ecosystem sustainability. Soil carbon storage, nutrient availability, and biogeochemical cycling depend on interactions among soil physical properties, microorganisms, and biological processes [22–24]. Microplastic accumulation may disturb these interactions by modifying soil structure, influencing soil organisms, and altering microbial activity and nutrient transformations [7, 8, 25]. However, the direction and magnitude of these effects vary considerably with particle characteristics, exposure concentrations, soil conditions, and agricultural management practices. This variability complicates the assessment of ecological risks and the development of effective management strategies, particularly when findings from controlled laboratory experiments are extrapolated to agricultural field conditions.

Despite increasing research attention, important knowledge gaps remain in understanding the relationships among MP sources, environmental behaviour, soil ecological responses, and agricultural sustainability. Existing studies frequently examine individual aspects of contamination, such as MP occurrence, transport, plant responses, microbial activity, or soil physicochemical changes, without consistently integrating these processes into a comprehensive assessment framework [21, 25, 28–32]. Furthermore, differences in exposure metrics, experimental conditions, and analytical approaches limit comparisons across studies. The implications of MP contamination for climate-smart agriculture, particularly agricultural productivity, climate adaptation, and greenhouse gas mitigation, also require more integrated evaluation.

The novelty of this review lies in its integrated source-to-consequence framework, which connects MP input pathways and exposure metrics with environmental transformation, transport, soil ecological effects, microbial and biogeochemical mechanisms, and agricultural

management responses. Unlike reviews focusing primarily on individual environmental compartments or biological endpoints, this study distinguishes MP abundance, agricultural plastic inputs, and environmental fluxes while examining how polymer properties, environmental ageing, soil characteristics, and hydrological processes influence MP behaviour. It also integrates evidence on microbial responses, carbon and nitrogen cycling, and climate-smart agricultural practices, with particular attention to differences between laboratory and field observations.

Accordingly, this review aims to critically synthesise existing evidence on the sources, occurrence, environmental fate, and ecological consequences of MPs in agricultural soils; evaluate the factors governing their persistence, mobility, and interactions with soil biological and biogeochemical processes; assess their implications for climate-smart agriculture; and identify research priorities and practical management strategies for reducing MP contamination and maintaining soil health. By integrating these dimensions, the review seeks to provide a scientific foundation for environmentally realistic risk assessment, sustainable agricultural management, and evidence-based policy development.

1.1. Research Gaps and Contributions of the Present Review.

Previous reviews have substantially advanced understanding of MP contamination in terrestrial and agricultural environments, although their research priorities and analytical perspectives differ. Earlier studies primarily addressed the emergence of plastic pollution in soils, its major sources, ecological consequences, and associated knowledge gaps [26, 27]. Subsequent reviews expanded the discussion to include soil physicochemical properties, environmental fate, and interactions with terrestrial organisms [8, 28]. More recent publications have examined MP occurrence in agricultural systems, plant responses, analytical methodologies, microbial health, and potential mitigation approaches [21, 25, 29–32].

Although these studies provide valuable insights, several limitations remain. First, MP abundance in soils, quantities of agricultural plastic inputs, and environmental transport fluxes are not always clearly distinguished, making comparisons across studies difficult. Second, the combined influences of polymer characteristics, particle ageing, soil texture, hydrological conditions, and agricultural practices on MP persistence and mobility require more systematic integration. Third, the relationships between MP-induced microbial changes and key biogeochemical processes, particularly carbon cycling and nitrogen transformations, remain insufficiently connected to broader agricultural sustainability outcomes. Finally, the implications of MP contamination for the three pillars of climate-smart agriculture—productivity, adaptation, and mitigation—have not been consistently evaluated within an integrated management framework.

To address these gaps, the present review introduces a comprehensive framework linking MP sources, environmental fate, soil ecological responses, microbial and biogeochemical mechanisms, climate-smart agriculture, and management strategies. Particular emphasis is placed on distinguishing exposure metrics, evaluating context-dependent environmental responses, comparing laboratory and field evidence, and identifying practical interventions ranging from pollution prevention to environmental monitoring. Table 1 compares the major contributions and limitations of previous reviews with the integrated

approach adopted in the present study, highlighting its contribution to understanding MP contamination and sustainable agricultural management [21, 25, 29–32].

Table 1. Comparison of Previous Reviews on Microplastics in Terrestrial and Agricultural Soils and The Contributions of the Present Review.

Review	Main research focus	Limitations relevant to the present review	Contribution of the present review
[26]	Soil plastic pollution, contamination sources, and ecological effects	Earlier evidence base with limited integration of quantitative findings and agricultural management	Incorporates recent evidence within a source-to-consequence framework
[8]	Sources, occurrence, environmental fate, and terrestrial risks	Broad terrestrial focus with limited emphasis on climate-smart agriculture	Links MP contamination to agricultural productivity, adaptation, mitigation, and management
[27]	Microplastics and nanoplastics in agroecosystems, ageing, and organismal responses	Limited coverage of more recent field and quantitative evidence	Integrates recent field observations and microbial and biogeochemical findings
[21]	Occurrence, sources, fate, analytical methods, and environmental impacts	Greater emphasis on analytical and occurrence-related aspects	Connects analytical variability with soil functions and sustainable management
[28]	Soil physical, chemical, and microbiological properties	Limited integration of contamination sources, transport processes, and management implementation	Connects environmental fate with soil ecological functions and management strategies
[29]	Microplastics and nanoplastics in agricultural soils, plant responses, and mitigation	Combined consideration of microplastics and nanoplastics, with emphasis on soil and plant effects	Focuses on MP evidence and integrates microbial processes, carbon and nitrogen cycling, and climate-smart agriculture
[30]	Agricultural MP sources, environmental fate, and ecological impacts	Limited distinction among exposure metrics and climate-smart agriculture dimensions	Differentiates abundance, input quantities, and environmental fluxes within an agricultural sustainability framework
[32]	Soil biological health, microbial interactions, and contaminant transport	Limited integration of physical transport mechanisms and broader management strategies	Links microbial responses with soil physical conditions, nutrient cycling, and agricultural decision-making
Present review	Integrated assessment of MP sources, fate, ecological effects, biogeochemical mechanisms, and management	—	Provides a source-to-consequence framework integrating exposure metrics, field realism, climate-smart agriculture, and prevention-to-monitoring strategies

1.2. Literature Review Methodology.

This study employed a structured narrative review approach to examine MP contamination and its implications for agricultural soil health and sustainability. Relevant literature was identified using Web of Science Core Collection, Scopus, PubMed, ScienceDirect, and Google Scholar as complementary indexing and literature discovery sources. The primary literature search covered publications from 2011 to 2026, while earlier foundational studies were included when necessary to establish essential concepts related to microplastics, polymer degradation, and soil processes. The search strategy was designed to enhance methodological transparency and selectively incorporated relevant reporting principles outlined in PRISMA 2020 [33].

Eligible publications included peer-reviewed research articles, meta-analyses, and review papers addressing MPs in terrestrial soils and agroecosystems. The literature covered contamination sources, occurrence, environmental fate, transport mechanisms, soil physicochemical properties, soil organisms, microbial communities, carbon and nutrient cycling, crop responses, and management strategies. Priority was given to field-based investigations and studies employing environmentally relevant exposure conditions.

Laboratory experiments and controlled pot studies were also considered when they provided mechanistic insights into MP behaviour and ecological effects [8, 21, 25, 28–32].

The selected literature was organised into thematic categories covering MP sources and input metrics, environmental transformation and transport, soil ecological consequences, microbial and biogeochemical mechanisms, quantitative evidence, climate-smart agriculture, and management approaches. Reported quantitative findings were retained in their original units and interpreted according to their respective experimental contexts rather than being combined across incompatible endpoints. Findings from published meta-analyses and experimental studies were compared by considering polymer composition, particle morphology and size, exposure concentration, soil characteristics, vegetation conditions, experimental duration, and laboratory versus field settings. Contradictory results were evaluated in relation to these contextual differences rather than interpreted as evidence of a universal positive or negative response [21, 25, 28–32].

2. Sources, Input Fluxes, and Pathways of Microplastics in Agricultural Soils

Microplastics reach agricultural soils through four broad routes: direct agricultural plastic use, waste-derived inputs, environmental deposition, and fragmentation of larger plastic already present in the soil. Unlike aquatic environments, where microplastics are often transported away, soils function as long-term sinks in which particles accumulate, persist, and undergo further transformation [11, 12]. Understanding these sources and pathways is essential for assessing ecological risks and designing sustainable management strategies.

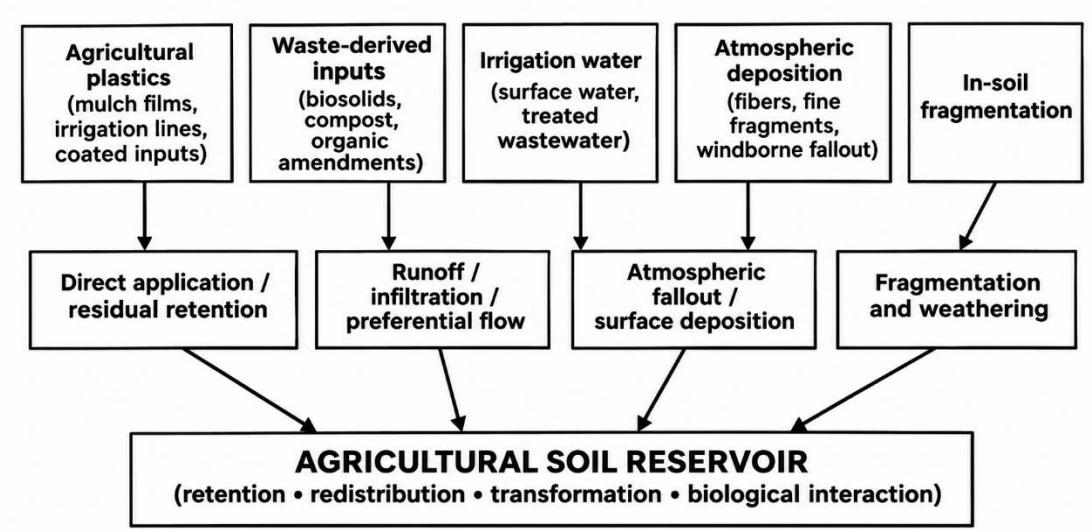


Figure 1. Schematic Illustration of the Principal Sources and Pathways by Which Microplastics Enter Agricultural Soils. The Diagram Separates Direct Agricultural Inputs, Waste-Derived Inputs, Environmental Delivery and In-Soil Fragmentation.

2.1 Agricultural Plastic Sources.

Mulch films, greenhouse and tunnel films, irrigation lines, pipes, silage materials and other agricultural plastics can become secondary microplastic sources after weathering and incomplete recovery. Mechanical abrasion, ultraviolet exposure, thermal cycling and repeated field operations progressively alter the polymer surface and promote fragmentation [12-14]. Polymer composition matters because polyethylene, polypropylene, polystyrene and other

polymers differ in density, crystallinity, additives, weathering behaviour and interaction with soil particles [21].

2.2 Waste-derived and Formulated Inputs.

Sewage sludge and biosolids can transfer microplastics captured during wastewater treatment to farmland, particularly synthetic fibres [11, 15]. Compost and other organic amendments may also contain plastic fragments and fibres when source separation and screening are incomplete [16]. Polymer-coated fertilisers and pesticide formulations represent another pathway because the coating may remain after the active ingredient has been released [11, 16]. These pathways link waste recycling and nutrient management with an unintended contaminant input and therefore require quality control rather than blanket assumptions that organic amendments are contaminant-free.

2.3 Environmental Inputs,

Irrigation water can repeatedly deliver microplastics to soil, with loading dependent on source-water concentration, irrigation volume and treatment efficiency [12, 21, 27]. Atmospheric deposition provides a diffuse pathway through airborne fibres and fragments released from urban areas, roads, waste handling and agricultural activities [17, 18]. Rainfall, surface runoff and wind erosion can subsequently redistribute particles between fields and adjacent environments. A summary of major source of microplastics in agricultural soil is shown in Table 2.

Table 2. Major source metrics for microplastics in agricultural soils.

Source/pathway	Metric type	Reported quantity	Unit	Interpretation	Ref.
Soil microplastic occurrence	Abundance	0–3.573 × 10^6 across reviewed soil studies	particles kg^{-1} soil	Measured soil abundance, not annual input flux	[21]
Sewage sludge/biosolids	Input quantity	63,000–430,000 deposited annually on European and North American farmland (estimated)	tonnes yr^{-1}	Estimated mass deposited, not microplastic particle abundance in soil	[11]
Agricultural plastics	Plastic-use context	12.5 million used globally in 2019	tonnes yr^{-1}	Total agricultural plastic use, not equivalent to microplastic formation	[19]
Food packaging in agri-food systems	Plastic-use context	37.3 million globally in 2019	tonnes yr^{-1}	Sector-wide plastic use, not a soil microplastic flux	[19]
Mulch films	Input/accumulation evidence	Major source; residues accumulate where retrieval is incomplete	Qualitative/regional estimates	Accumulation varies with film use, retrieval efficiency, and soil management history	[13, 14]
Atmospheric deposition	Environmental deposition	Continuous atmospheric deposition documented	particles m^{-2} d^{-1}	Deposition flux; site-specific values are not directly comparable with soil abundance	[17, 18]
Irrigation water	Waterborne concentration	Repeated inputs from treated wastewater and surface water	particles L^{-1}	Water concentration; soil loading also depends on irrigation volume	[12, 21, 27]

The available evidence therefore supports a source hierarchy rather than a single global input value. Plasticulture, sludge and organic amendments, irrigation and atmospheric deposition can all contribute, but their relative importance varies among farming systems and regions. Methodological differences in sampling depth, particle-size cut-offs, density separation and polymer identification further limit direct comparison among field studies [21]. Differences in analytical procedures, sampling approaches and the soil fractions examined can also contribute to apparent variation in reported soil abundance [21, 34, 35].

3. Transformation, Ageing and Transport in Agricultural Soils

Once introduced into agricultural soils, microplastics undergo physical, chemical, and biological processes, including fragmentation, surface oxidation, biofilm formation, aggregation, and redistribution. Their environmental behaviour depends on interactions between particle characteristics and soil properties rather than particle concentration alone. Polymer density, crystallinity, additives, particle size, shape, and surface chemistry influence sorption, weathering, and mobility, while soil texture, organic matter, aggregation, pore structure, pH, and moisture conditions regulate retention and transport [8, 21, 36].

3.1. Ageing and Fragmentation.

Environmental ageing modifies microplastic surfaces through oxidation, mechanical abrasion, and biological interactions. Ultraviolet radiation can initiate photo-oxidation at exposed soil surfaces, while temperature fluctuations, tillage, agricultural machinery, root growth, and wet–dry cycles contribute to physical deterioration and fragmentation [13, 14, 21, 26]. These processes may increase surface roughness and introduce oxygen-containing functional groups, altering interactions with soil colloids and other contaminants. However, fragmentation should not be confused with complete polymer degradation. For many conventional plastics, environmental ageing primarily produces smaller particles and modifies surface characteristics rather than rapidly converting polymers into carbon dioxide and water. Consequently, microplastics may persist in agricultural soils while undergoing progressive changes in their physical and chemical properties [20, 21, 26].

3.2. Transport and Retention.

Microplastics can be redistributed through surface runoff, wind erosion, infiltration, preferential flow, root channels, soil-fauna activity, and agricultural operations. Their mobility depends on particle size, density, shape, and surface properties, together with soil texture, pore connectivity, aggregation, and hydrological conditions [21, 37, 38]. Although smaller particles generally have greater transport potential, particle size alone does not determine mobility. Experimental studies have demonstrated vertical microplastic migration, particularly in sandy soils and under repeated wet–dry cycles [37]. Field investigations further indicate that crop type, seasonal conditions, and soil characteristics influence microplastic distribution and ecological exposure [39, 40]. Agricultural practices, including tillage and irrigation, may enhance redistribution by modifying soil structure and water movement. Nevertheless, comparative evidence on the effects of different tillage systems remains limited, and migration rates cannot be generalized across contrasting agricultural environments [21, 38, 39]. Figure 2 illustrates the principal processes governing microplastic

transformation, retention, and redistribution in agricultural soils. The conceptual framework integrates particle characteristics, soil properties, hydrological conditions, and agricultural management practices to explain the variability in microplastic behaviour.

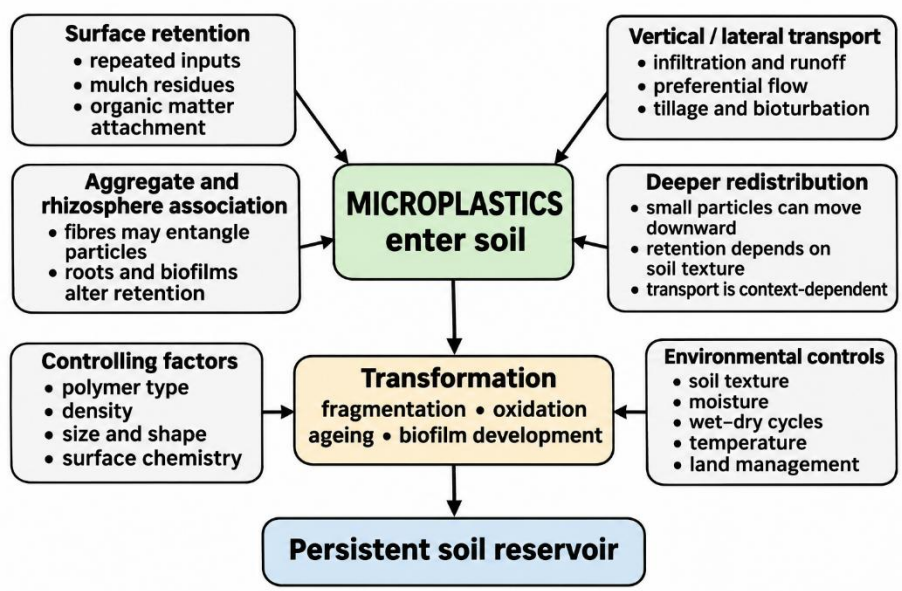


Figure 2. Conceptual framework illustrating microplastic ageing, transformation, transport, and retention in agricultural soils.

As illustrated in Figure 2, microplastic fate is controlled by interconnected physical and chemical processes rather than a single transport mechanism. Particle fragmentation and surface modification may alter mobility and retention, while soil structure and water movement determine redistribution pathways. These interactions highlight the importance of evaluating microplastic behaviour under site-specific environmental conditions [21, 37, 38].

4. Ecological Behaviour and Soil-Level Consequences

Microplastics can influence soil ecological functioning through changes in physical structure, water dynamics, biological interactions, and contaminant behaviour. The magnitude and direction of these effects depend on polymer characteristics, exposure concentration, soil properties, and environmental conditions.

4.1. Soil Physical Structure and Aggregation.

Microplastics can become incorporated into soil aggregates or occupy pore spaces, potentially modifying bulk density, porosity, aggregate stability, and pore connectivity. Low-density polymers, including polyethylene (PE) and polypropylene (PP), may reduce measured bulk density and increase total porosity. However, these changes do not necessarily indicate improved soil structure because pore distribution and connectivity may also be altered [41, 42]. Particle shape further influences soil physical responses. Fibres may entangle soil particles and modify aggregation, whereas fragments and films can disrupt aggregate continuity or alter pore structure. Experimental findings indicate that these effects vary with polymer composition, particle geometry, concentration, and soil characteristics [31, 36].

Consequently, particle shape and form should be considered important exposure descriptors when evaluating microplastic impacts on soil structure [43].

4.2. Water Retention, Infiltration, and Hydraulic Conductivity.

Changes in soil aggregation and pore structure may influence water retention, infiltration, and hydraulic conductivity. Experimental studies have reported modifications in soil water-holding capacity and hydraulic behaviour following microplastic exposure, although the direction and magnitude of responses vary among soil types and particle characteristics [41, 42]. These changes may affect agricultural water availability and the movement of dissolved nutrients or contaminants. For example, altered pore connectivity may increase water retention under certain conditions or promote preferential flow under others. Therefore, potential implications for drought resilience and heavy-rainfall responses should be evaluated using measured hydraulic properties rather than inferred solely from microplastic occurrence.

4.3. Soil Fauna and Rhizosphere Processes.

Soil fauna contribute to microplastic redistribution through ingestion, burrowing, and casting. Earthworm exposure experiments have reported changes in growth, behaviour, and gut-associated microbial communities, indicating potential interactions between microplastics and soil biological processes [44, 45]. In the rhizosphere, microplastics may accumulate near plant roots and interact with root exudates, microbial biofilms, and surrounding soil particles. These interactions can modify microscale habitats and potentially influence nutrient availability and carbon transformations. However, their ecological significance under realistic agricultural field conditions remains incompletely understood [7, 38].

4.4. Chemical Interactions and Co-contaminants.

Microplastic surfaces can sorb hydrophobic organic contaminants, as demonstrated in aqueous systems and broader investigations of microplastic and nanoplastic sorption behaviour [9, 10]. In agricultural soils, polymer ageing and surface modification may further influence contaminant attachment, mobility, and bioavailability. These interactions depend on polymer composition, particle condition, contaminant chemistry, and soil characteristics [8, 21]. Consequently, microplastics should not be assumed to consistently increase contaminant toxicity or mobility. Environmental risk assessment should instead consider combined exposure conditions and the specific mechanisms governing contaminant–particle interactions.

5. Microbial and Biogeochemical Mechanisms

Microplastic exposure can influence soil microbial communities and biogeochemical processes through changes in habitat structure, surface chemistry, moisture availability, and interactions with contaminants. However, microbial responses are highly variable because polymer identity, particle size, shape, concentration, and environmental conditions interact to determine exposure effects [31, 42, 46–49]. Table 3 summarizes comparative evidence on the effects of microplastic shape, size, and polymer type on soil physicochemical properties and microbial responses.

Table 3. Comparative evidence on microplastic shape, size, and polymer type in relation to soil physicochemical properties and microbial responses.

Characteristic	Category	Reported soil physicochemical response	Reported microbial response	Interpretive limitation	Ref.
Shape	Fibres	May alter pore structure, water distribution, and aggregation	Changes in microbial activity and community structure depend on polymer and concentration	Effects interact with polymer, dose, and soil texture	[31, 42, 46]
Shape	Films	May reduce bulk density, alter water pathways, and decrease aggregation	PE films may modify enzyme activity and bacterial community composition	Geometry and polymer chemistry interact	[31, 46]
Shape	Fragments	May disrupt aggregates and modify porosity	Responses vary with polymer and exposure duration	Particle size distributions are not consistently reported	[31, 46]
Size	<50 μm	Greater potential mobility and interactions with pore networks and sorption surfaces	May alter microbial exposure and community composition	Experimental concentrations may exceed field levels	[21, 37, 41, 47, 49]
Size	50–150 μm	May modify aggregation and pore structure	Responses depend on polymer, size, and exposure duration	No universal size threshold	[21, 37, 41, 47, 49]
Size	>150 μm	Generally lower mobility but may influence aggregation and water flow	Responses may differ from those induced by smaller particles	Effects depend on geometry and concentration	[21, 37, 41, 47, 49]
Polymer	PE/LDPE	May modify bulk density, porosity, and aggregation	May alter bacterial communities and nitrogen-related processes	Ageing and additives influence responses	[31, 41, 46, 49]
Polymer	PP	May affect aggregation, pore structure, and plant–soil interactions	Responses may differ from those associated with PE	Polymer and shape effects may overlap	[31, 32, 49]
Polymer	PVC	May modify soil pH and enzyme-related processes	Reduced bacterial diversity reported under some conditions	Strongly dependent on concentration and soil conditions	[28, 46]
Polymer	PS	May influence aggregation and other physical properties	May alter microbial activity and interactions with co-contaminants	Often investigated at elevated experimental concentrations	[28, 31, 49]
Polymer	PLA/biodegradable polymers	May produce physical and nutrient responses that differ from conventional polymers	Some studies report stronger enzyme responses	Biodegradability does not eliminate short-term ecological effects	[32, 40, 48, 50]

Note: PE = polyethylene; LDPE = low-density polyethylene; PP = polypropylene; PVC = polyvinyl chloride; PS = polystyrene; PLA = polylactic acid. All original references have been consolidated into the rightmost column, with their numbering preserved.

As shown in Table 3, microplastic characteristics influence soil physicochemical properties and microbial responses through interacting mechanisms. Fibres, films, and fragments differ in their effects on aggregation and pore structure, while particle size influences potential mobility and microbial exposure. Polymer-specific responses are also evident, although differences in concentration, ageing, soil properties, and experimental conditions limit direct comparisons among studies [31, 42, 46–49].

5.1. Microplastic and Soil Properties as Exposure Modifiers.

Polymer identity, particle size, shape, surface chemistry, and environmental ageing influence microbial exposure by modifying particle attachment, sorption, and interactions with surrounding soil components. Ageing may increase surface roughness and introduce oxygen-containing functional groups, while smaller particles generally provide a greater surface-area-to-volume ratio and potentially more extensive contact with microorganisms and co-

contaminants [8, 14, 21, 25]. Soil properties further regulate these interactions. Texture, organic matter, pH, moisture, and aggregation influence particle retention, microbial habitats, and substrate availability. Clay content and soil pH can modify enzyme responses, while organic carbon and nutrient availability affect microbial activity. Consequently, identical microplastic treatments may produce contrasting outcomes across different soil environments [21, 36, 47].

5.2. Plant and Soil-Fauna Mediation.

Plants and soil fauna influence microplastic exposure through changes in soil structure, particle redistribution, and microbial habitat conditions. Root growth and rhizosphere exudates modify microscale environments, while earthworms redistribute particles through ingestion, burrowing, and casting [44, 45]. Plant presence may also moderate microbial responses to microplastic exposure. Some studies have reported weaker enzyme responses in planted systems than in plant-free experimental conditions [50]. These findings emphasize the importance of incorporating plant–soil interactions into experimental designs when evaluating ecological responses under agricultural conditions.

5.3. Microbial Habitat, Community Structure, and Functional Responses.

Microplastics can alter soil microbial habitats by modifying pore structure, moisture distribution, surface availability, and interactions with organic substrates or contaminants. These changes may influence microbial community composition, diversity, biomass, and extracellular enzyme activities [25, 46, 51]. A global hierarchical meta-analysis involving 117 publications and 2,160 datasets reported significant reductions in bacterial diversity and richness, together with contrasting effects on nitrogen-cycle processes. Nitrification was inhibited, whereas ammonium assimilation, nitrogen fixation, and urea decomposition increased under the conditions represented in the synthesis [49]. Earlier studies also documented interactions between microplastics, plants, fungi, and soil microbial communities [26, 52, 53]. Changes in microbial community composition do not necessarily correspond to proportional changes in microbial biomass or functional activity. Microplastic exposure may favour microorganisms adapted to altered surfaces, moisture conditions, or contaminant availability, thereby changing community structure and functional potential [49, 51, 54, 55]. Microbial functional responses may also involve changes in extracellular enzyme activity, organic matter decomposition, and nutrient transformation. However, the direction and magnitude of these effects depend on polymer characteristics, exposure concentration, soil conditions, plant presence, and experimental duration [46, 47, 50].

5.4. Experimental Conditions and Exposure Realism.

Experimental concentration, exposure duration, and study design contribute substantially to differences in reported microbial responses. Laboratory incubation and pot experiments provide controlled conditions for investigating mechanisms but may employ microplastic concentrations that exceed those typically measured in agricultural soils. Recent evidence syntheses indicate that average responses under field conditions may be weaker or less consistent than those observed in controlled experiments. This discrepancy highlights the

importance of distinguishing experimentally induced effects from responses likely to occur under realistic environmental exposure [40, 48].

5.5. Mechanistic Relationships Between Microbial Responses and Soil Functions.

Microplastics may influence soil biogeochemical functioning through interconnected physical, chemical, and biological mechanisms. Changes in soil structure, moisture distribution, particle surfaces, and microbial colonization can modify microbial community composition and enzyme activity, potentially affecting organic carbon processing and nutrient transformations [46, 47, 49, 50, 56]. Figure 3 presents a conceptual framework linking microplastic exposure to changes in microbial habitats, community structure, enzyme activities, carbon cycling, and nitrogen transformation.

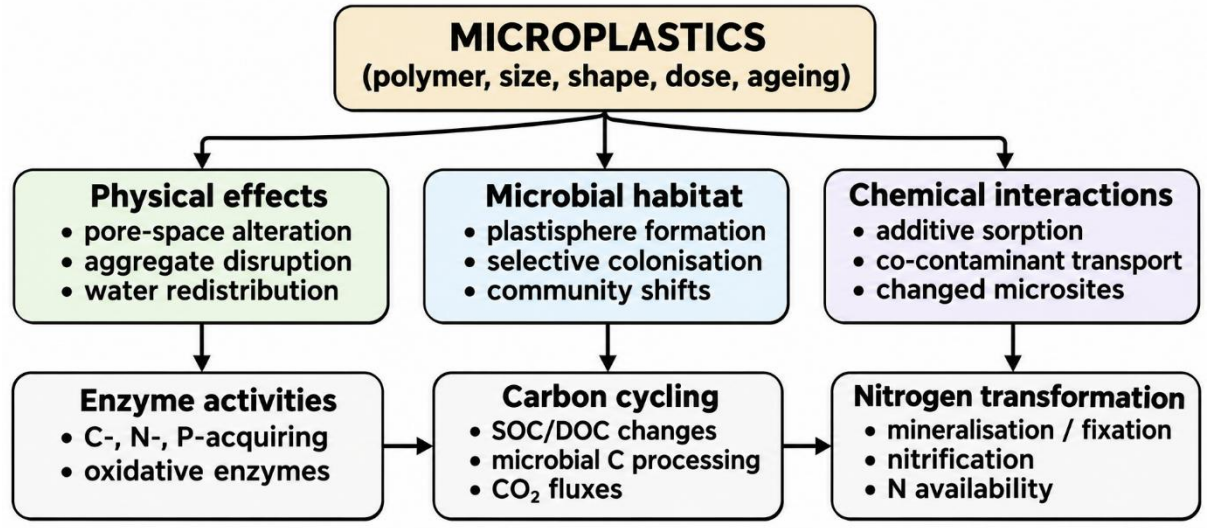


Figure 3. Mechanistic Framework Linking Microplastic Exposure to Soil Microbial Communities, Enzyme Activities, Carbon Cycling, and Nitrogen Transformation. The Pathways Represent Evidence-Supported Conceptual Relationships, While The Direction And Magnitude of Individual Responses Depend on Environmental Conditions.

As illustrated in Figure 3, microplastic exposure may initiate changes in soil physical and chemical microsites, followed by shifts in microbial communities and enzymatic processes. These responses can influence carbon and nitrogen transformations and ultimately affect soil multifunctionality. However, the relationships are context-dependent and should not be interpreted as a universal sequence of adverse effects [46, 47, 49, 50, 56].

5.6. Carbon, Nitrogen, and Phosphorus Cycling.

Microplastic exposure can influence soil carbon dynamics by modifying microbial activity, organic matter decomposition, and carbon transformation processes. A global meta-analysis covering 180 publications and 3,338 paired observations reported increases in soil total carbon, soil organic carbon, microbial biomass carbon, and dissolved organic carbon, alongside a 25.7% increase in soil CO_2 emissions. The same synthesis reported reductions in nitrate nitrogen, ammonia volatilization, and aboveground plant biomass [56]. A separate global meta-analysis reported increases of 21% in soil organic carbon, 12% in dissolved organic carbon, 17% in microbial biomass, and 25% in soil CO_2 emissions, accompanied by a 3% reduction in microbial diversity [57]. These findings demonstrate that increases in soil

carbon pools may occur alongside greater respiratory carbon losses. Therefore, changes in carbon storage and carbon emissions should be evaluated as distinct outcomes rather than interpreted as equivalent indicators of carbon sequestration.

Nitrogen cycling responses are similarly heterogeneous. A hierarchical meta-analysis reported reduced nitrification but increased ammonium assimilation, nitrogen fixation, and urea decomposition following microplastic exposure [49]. Another synthesis of 147 studies and 1,138 observations reported increases of 7.6% in urease activity and 8.0% in leucine aminopeptidase activity. These responses were influenced by polymer type, particle size, concentration, experimental conditions, soil pH, clay content, organic carbon, and total nitrogen [47]. A 2026 meta-analysis covering 206 studies and 2,853 observations reported average reductions of 5.3% in available nitrogen, 9.4% in available phosphorus, and 7.0% in available potassium, primarily in controlled experiments. Importantly, nutrient depletion was observed in pot and incubation studies, whereas field studies did not show statistically significant changes [48]. This distinction reinforces the need for caution when extrapolating laboratory findings to agricultural field conditions. Overall, the available evidence indicates that microplastics can influence soil microbial functioning, carbon dynamics, and nutrient cycling through multiple interacting pathways. However, the magnitude and direction of these responses vary according to polymer properties, exposure concentrations, soil characteristics, biological interactions, and experimental settings. Therefore, microplastic impacts on soil functioning should be evaluated using context-specific evidence rather than assuming consistent ecological outcomes across agricultural environments [46–49, 56].

6. Quantitative Synthesis of Reported Effects

Quantitative evidence on microplastic impacts in agricultural soils varies considerably across studies because of differences in polymer composition, particle size, exposure concentration, experimental duration, and environmental conditions. Therefore, reported effects should be interpreted within their respective experimental contexts rather than combined into a universal response. Previous meta-analytical research has identified measurable but heterogeneous changes in soil physicochemical properties and nutrient dynamics [58]. Table 4 summarizes major quantitative findings from recent meta-analyses and field experiments, highlighting their direction, magnitude, and methodological limitations. microplastics influence plant productivity, microbial communities, enzyme activities, nutrient availability, and carbon dynamics, although the magnitude and direction of these effects differ substantially. Meta-analyses generally identify measurable changes across multiple soil functions, whereas field studies frequently report weaker, neutral, or context-dependent responses [40, 48]. These differences emphasize the importance of considering exposure concentration, polymer characteristics, soil properties, and experimental design when interpreting ecological risks.

Table 4. Quantitative Findings From Recent Meta-Analyses and Field Experiments.

Exposure or dataset	Direction of effect	Quantitative finding	Context and limitations	Ref.
128 studies; ecosystem-service meta-analysis	Mixed	Plant productivity −14.5%; microbial biodiversity −3.4%; soil fertility −8.2%; soil carbon sequestration +12.2%	Responses differed among ecosystem-service categories	[55]
Global meta-analysis of soil microbiomes and CO_2 emissions	Mixed	SOC +21%; DOC +12%; microbial biomass +17%; soil CO_2 emissions +25%; microbial diversity −3%	Carbon pools increased alongside respiratory carbon losses	[57]
72 publications; 453 paired observations	Mixed	N-acquiring enzymes +4%; P-acquiring enzymes +14%; oxidative enzymes +8%; C-acquiring enzymes −2%	Laboratory-based evidence; biodegradable polymers produced stronger enzyme responses	[50]
147 studies; 1,138 observations	Positive/mixed	Urease +7.6%; leucine aminopeptidase +8.0%; N-acetyl-β-D-glucosaminidase showed no significant change	Responses depended on soil pH, clay content, polymer characteristics, and experimental conditions	[47]
Two-year field trial; PE at 0, 100, and 600 mg kg^{-1}	Mixed	PE at 600 mg kg^{-1} increased rice grain weight by 42.5%; available P and N forms declined during relevant seasons	Responses differed between rice and wheat	[39]
Two-year field trial; PP and PLA fibres	Negative/neutral	PP reduced oat yield by 15.5–17.5%; PLA showed no significant yield reduction	Conventional and biodegradable polymers produced different field responses	[59]
206 studies; 2,853 observations	Negative overall; neutral in field studies	Available N −5.3%; P −9.4%; K −7.0%	Overall effects were largely driven by pot and incubation studies; field effects were not significant	[48]
Five-year, four-site field experiment and field-only global synthesis	Neutral/weak average	At 0.2% w/w loading, no consistent negative functional responses were observed across crops, sites, and years	Field responses were heterogeneous and generally weaker than laboratory findings	[40]

Note: SOC = soil organic carbon; DOC = dissolved organic carbon; PE = polyethylene; PP = polypropylene; PLA = polylactic acid. Positive and negative values indicate reported increases and decreases, respectively, relative to the comparison conditions.

Differences among studies can largely be attributed to variations in exposure conditions and environmental characteristics. Laboratory and pot experiments often use relatively high or uniform microplastic concentrations, whereas field environments incorporate spatial heterogeneity, plant–soil interactions, weather variability, and agricultural management. Recent field-focused evidence indicates that average ecological responses are frequently weaker than those observed under controlled conditions [40, 48].mParticle characteristics also influence experimental outcomes. Polymer identity, shape, size, and ageing affect soil pore interactions, sorption behaviour, microbial colonization, and enzyme activities [31, 42, 47]. Soil properties, including pH, clay content, organic carbon, texture, and moisture, further modify particle retention and biological responses. Plant presence may also moderate some microplastic-induced effects [47–50]. Consequently, apparently contrasting findings do not necessarily indicate scientific inconsistency. For example, increases in soil carbon pools may occur alongside greater respiratory carbon losses, while changes in nutrient availability may differ among crops and experimental systems. The available evidence therefore supports a context-dependent interpretation of microplastic effects rather than a universal positive or negative response [21, 39, 40, 47–50, 55, 56, 59].

7. Implications for Climate-Smart Agriculture.

Climate-smart agriculture (CSA) encompasses three interconnected objectives: improving agricultural productivity, strengthening adaptation and resilience, and supporting climate-change mitigation. Microplastic contamination may influence each objective through different soil processes, although the strength and consistency of available evidence vary. Figure 4 illustrates the conceptual relationships between microplastic exposure and the three CSA pillars, distinguishing their respective mechanisms and potential outcomes.

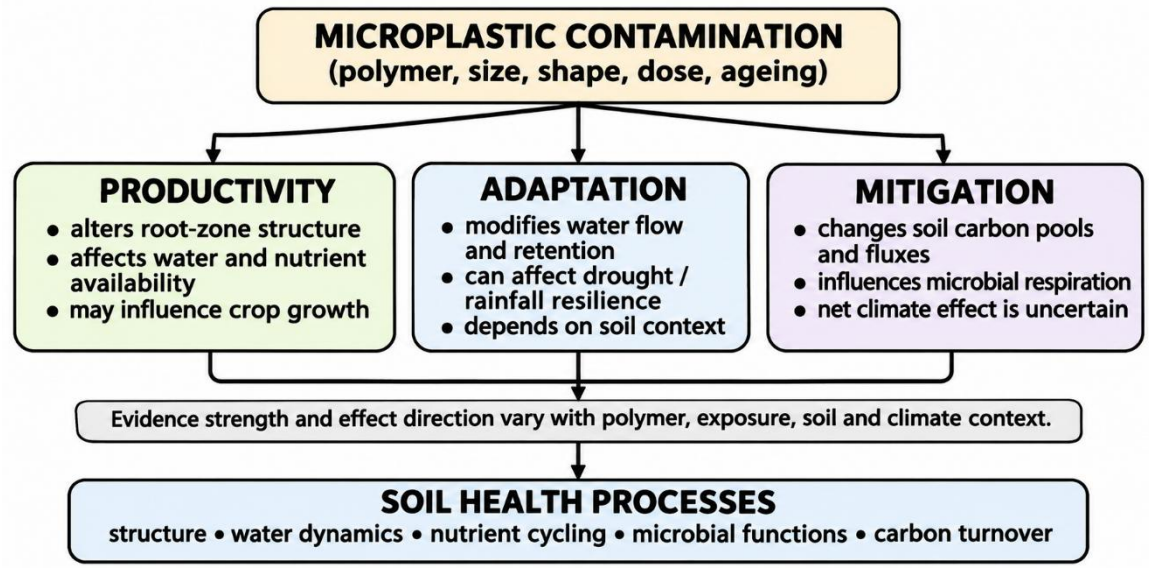


Figure 4. Conceptual Framework Illustrating the Potential Effects of Microplastic Contamination on the Three Pillars o Climate-Smart Agriculture: Productivity, Adaptation, and Mitigation.

7.1. Agricultural Productivity.

Microplastics may influence crop productivity by modifying soil structure, nutrient availability, water dynamics, and microbial functioning. A meta-analysis reported an average reduction of 14.5% in plant productivity [55]. However, field experiments have demonstrated contrasting responses depending on polymer type, crop species, and exposure conditions. For example, a two-year field study reported a 15.5–17.5% reduction in oat yield following polypropylene exposure, whereas polylactic-acid microplastics did not significantly affect yield [59]. Conversely, polyethylene exposure increased rice grain weight by 42.5% under one experimental treatment, despite reductions in certain soil nutrient pools [39]. These findings indicate that productivity responses cannot be predicted from individual soil indicators and require crop-specific field evaluation.

7.2. Climate Adaptation and Soil Resilience.

Soil resilience depends on the capacity to maintain structural stability, water availability, and nutrient cycling under environmental stress. Microplastics can alter soil porosity, aggregation, and hydraulic properties, potentially influencing responses to drought and heavy rainfall [41, 42, 60, 61]. However, these effects vary with soil texture, polymer characteristics, particle concentration, and moisture conditions. Experimental studies investigating microplastic–drought interactions suggest that microplastics may modify plant and soil responses to water stress [60, 61]. Nevertheless, current evidence does not establish a

consistent reduction in climate adaptation capacity across agricultural systems. Site-specific assessment is therefore necessary to determine whether observed physical changes translate into meaningful differences in soil resilience [21, 41, 42].

7.3. Climate-Change Mitigation.

Microplastic contamination may influence climate-change mitigation through changes in soil carbon storage, microbial decomposition, and greenhouse-gas emissions. One meta-analysis reported a 25.7% increase in soil CO_2 emissions alongside changes in soil carbon pools [56]. Another synthesis identified increases in soil organic carbon, dissolved organic carbon, and microbial biomass, accompanied by a 25% increase in soil CO_2 emissions [57]. These findings indicate that changes in carbon storage and respiratory carbon losses can occur simultaneously. Therefore, increased soil carbon content should not automatically be interpreted as improved climate mitigation. The net effect depends on carbon stabilization, microbial activity, decomposition processes, and greenhouse-gas fluxes. Further field-based investigations are required to establish the long-term implications of microplastic exposure for agricultural carbon balances.

8. Mitigation Framework and Future Research Priorities

Managing microplastic contamination in agricultural soils requires an integrated approach emphasizing source prevention, responsible agricultural practices, environmental monitoring, and policy development. Because microplastics can persist and become widely dispersed within soil matrices, preventing additional inputs is generally more practical than attempting complete removal. Management strategies should therefore prioritize reducing new contamination while limiting the redistribution and potential ecological effects of existing particles [19, 21, 27].

8.1. Source Reduction and Agricultural Plastic Management.

Source prevention should prioritize the collection, recovery, and appropriate disposal of agricultural plastics, including mulch films, irrigation materials, and greenhouse coverings. Improved collection infrastructure, recycling systems, and producer responsibility can reduce plastic residues available for environmental fragmentation [19]. Uncontrolled burning, burial, and mechanical shredding should be discouraged because they may introduce additional contaminants, generate smaller plastic fragments, or redistribute existing residues. Effective management requires coordinated participation among farmers, agricultural suppliers, waste-management operators, and regulatory authorities.

8.2. Biodegradable and Bio-Based Mulch Films.

Biodegradable mulch films have been proposed as alternatives to conventional polyethylene products. However, their environmental performance depends on polymer composition, soil conditions, temperature, moisture, and degradation processes. Incomplete degradation may leave residual fragments, indicating that biodegradability should not be considered equivalent to the absence of ecological risk [62, 63]. Field evidence also suggests that biodegradable polymers do not consistently produce more favourable ecological outcomes across all soil

functions [40]. Therefore, their application should be supported by appropriate certification, end-of-life management, and field-based monitoring.

8.3. Soil Management and Contaminated Amendments.

Agricultural soil management should minimize additional microplastic inputs and unnecessary particle redistribution. Organic fertilizers, compost, biosolids, and other waste-derived amendments may introduce microplastics when source separation and treatment processes are inadequate [15, 16]. Accordingly, amendment management should emphasize source-quality verification, appropriate application rates, and contamination monitoring. Maintaining soil structure and reducing unnecessary disturbance may help limit redistribution, although the effectiveness of specific tillage practices for microplastic control requires further validation.

8.4. Irrigation and Sludge Management.

Wastewater reuse and sludge application require effective controls to minimize microplastic loading. Advanced wastewater treatment technologies can reduce particle concentrations, although complete removal is not guaranteed [27]. Irrigation management should consider both microplastic concentrations in source water and the total volume applied. Similarly, sludge quality standards and application limits can help reduce cumulative contamination. These measures should be supported by routine monitoring of irrigation water, sludge, and agricultural soils.

8.5. Monitoring and Environmental Risk Assessment.

Reliable microplastic monitoring requires standardized sampling, particle identification, quality assurance, and reporting procedures. Important parameters include sampling depth, particle size distribution, polymer composition, abundance, and mass concentration. Environmental fluxes should be reported separately from soil concentrations to avoid misleading comparisons [21]. Monitoring programmes should also document soil texture, organic matter, pH, land use, tillage, irrigation practices, and amendment history. Integrating these variables would improve the interpretation of microplastic distribution, ecological exposure, and long-term contamination trends.

8.6. Policy, Governance, and Farmer Education.

Effective governance should combine agricultural plastic reduction, product standards, environmental monitoring, and farmer education. Regulatory thresholds should be developed using environmentally realistic exposure information rather than relying on isolated laboratory endpoints, as recent quantitative syntheses demonstrate substantial variation across soil conditions and experimental settings [40, 47, 48]. Risk-based policies should prioritize high-input pathways and support harmonized monitoring programmes, while educational initiatives can encourage responsible plastic use, collection, and disposal [19, 27]. Table 5 compares the principal management strategies for microplastics in agricultural soils, highlighting their expected benefits, limitations, and implementation challenges.

Table 5. Comparison of Management Strategies for Microplastics in Agricultural Soils.

Management strategy	Expected benefits	Limitations	Implementation challenges	Ref.
Source prevention and plastic recovery	Reduces new microplastic inputs and future fragmentation	Does not remove existing soil contamination	Collection systems, farmer participation, recycling infrastructure, and producer responsibility	[19, 21]
Certified biodegradable/bio-based films	May reduce the persistence of conventional plastic residues	Degradation depends on polymer and soil conditions; fragments may remain	Certification, field verification, end-of-life standards, and cost	[40, 62, 63]
Quality control of compost and biosolids	Reduces contamination from waste-derived amendments	Does not address legacy contamination	Routine testing, source separation, and enforceable quality standards	[16, 21, 27]
Irrigation management	Reduces microplastic loading from contaminated water and may limit redistribution	Treatment does not guarantee complete removal	Water-quality monitoring, treatment capacity, and irrigation efficiency	[12, 21, 27]
Soil management and reduced disturbance	May help limit particle redistribution and maintain soil structure	Does not remove existing particles; benefits of specific tillage systems remain uncertain	Balancing soil conservation with crop establishment and weed management	[38, 39]
Monitoring and standardized assessment	Improves data comparability, trend detection, and environmental risk assessment	Sampling and polymer identification may be expensive	Harmonized methods, quality assurance, laboratory capacity, and long-term datasets	[21, 34, 35]
Policy, standards, and farmer education	Encourages preventive practices and consistent environmental management	Requires regulatory coordination and evidence-based thresholds	Institutional coordination, enforcement, awareness, and technical guidance	[19, 27, 40]

As summarized in Table 5, source prevention and plastic recovery provide the most direct opportunities to reduce additional contamination, whereas soil management and irrigation controls primarily address ongoing inputs and particle redistribution. Monitoring and policy measures support these interventions by improving contamination assessment, implementation consistency, and long-term evaluation. However, no single strategy can comprehensively address microplastic contamination, emphasizing the need for integrated and locally adapted management approaches.

8.7. Research Needs and Future Directions.

Future research should prioritize long-term field experiments using environmentally realistic microplastic concentrations and representative agricultural conditions. Multi-year studies comparing conventional and biodegradable polymers are particularly important for evaluating persistence, ecological effects, and crop responses. Experimental designs should consistently report polymer identity, particle size and shape, ageing status, soil characteristics, climate conditions, crop management, and exposure duration [21, 40]. Mechanistic investigations should integrate microbial community composition, enzyme activities, carbon fluxes, nitrogen transformations, and agronomic outcomes. This approach is necessary because microbial biomass, diversity, and functional responses may change independently [47, 49, 50, 55]. Additional research should examine interactions between microplastics and drought, fertilization, pesticides, and soil organic matter under realistic field conditions. Figure 5 presents the proposed mitigation framework, integrating source prevention, soil management, environmental monitoring, and policy interventions. Research and technological development

support these components by improving exposure assessment, identifying effective management practices, and evaluating long-term environmental outcomes.

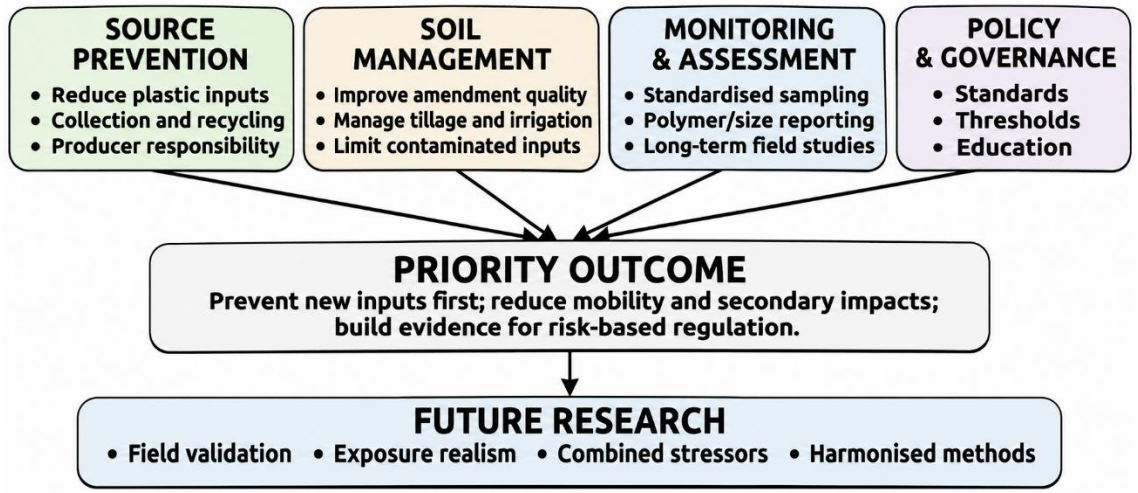


Figure 5. Integrated Mitigation Framework for Microplastic Contamination in Agricultural Soils, Highlighting Source Prevention, Soil Management, Environmental Monitoring, Policy Interventions, and Supporting Research Priorities.

The framework illustrated in Figure 5 emphasizes prevention as the primary management priority, supported by practices that reduce additional inputs and limit particle redistribution. Monitoring provides the evidence required to evaluate intervention outcomes, while policy and education promote consistent implementation. Long-term field research remains essential for determining which strategies provide measurable environmental and agricultural benefits under different soil and management conditions.

9. Conclusions

The evidence reviewed here supports the conclusion that microplastics are a persistent and potentially important stressor in agricultural soils, but their ecological effects are not uniform. The most defensible evidence-based interpretation is that polymer properties, particle characteristics, soil texture, hydrology, agricultural management, and exposure duration jointly determine outcomes. Quantitative syntheses document measurable changes in plant productivity, nutrient availability, microbial diversity, enzyme activities and carbon processes, while recent field evidence demonstrates that laboratory responses can be weaker, stronger or qualitatively different under realistic agricultural conditions [21, 39, 47-50, 55, 56, 59]. Management should therefore prioritise prevention of new inputs, especially from agricultural plastics, contaminated amendments and irrigation sources. Soil management, monitoring and policy should complement source reduction rather than substitute for it. Claims that biodegradable materials or soil amendments automatically eliminate risk are not supported by the current evidence and should be replaced by polymer- and context-specific evaluation [40, 62, 63]. The principal research limitation is the heterogeneity of existing evidence, including differences in analytical methods, exposure concentrations, polymer types, particle sizes, soil properties and experimental duration. Future priorities are harmonised measurement, long-term field validation, realistic exposure scenarios, mechanistic linkage of microbial and biogeochemical processes, and integrated assessment of crop productivity, soil health and climate resilience. These priorities would improve the

scientific basis for risk governance while avoiding overgeneralisation from simplified experimental systems.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Author Contribution

Joseph Ekenwosu did the conceptualization, analysis, literature review, writing, and prepared the manuscript. Editing, revision, and proofreading was done by Ann Gunina. Authors read the manuscript and approved it for publication.

Data Availability Statement

No new primary dataset was generated for this review. The evidence synthesised in the article is derived from the published studies cited in the reference list.

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