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Impacts of Microplastic Pollution on Soil Ecosystems and Agricultural Productivity

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ABSTRACT

The pervasive use of plastics has resulted in widespread contamination of agricultural soils by microplastics (MPs, <5 mm). These particles impair crop growth, infiltrate the global food web, and pose a rising threat to agricultural productivity and food security. This review synthesizes data from field surveys and controlled experiments to (1) compare major pathways of MP accumulation—plastic mulching, sewage sludge application, compost amendments, irrigation, and atmospheric deposition; (2) evaluate impacts on soil physicochemical properties; and (3) assess direct effects on seed viability, seedling biomass, plant water uptake, and contaminant transfer. Evidence indicates that MPs may contribute to a projected 5–15% decline in crop yields in the coming decades. However, these effects are dose-dependent, type-specific, and strongly influenced by soil context. Significant research gaps remain, including the lack of standardized detection and quantification protocols, limited long-term and field-scale studies, and inadequate policy and management strategies. Addressing these challenges requires coordinated, interdisciplinary approaches integrating environmental science, agronomy, and policy development. The review concludes by outlining mitigation strategies for MP pollution in agriculture and soil biota, and by identifying priority research directions to clarify poorly understood mechanisms and inform effective interventions.

Keywords — Microplastics, agricultural productivity, soil ecosystems, crop yields, plastic mulching, sewage sludge, irrigation, soil characteristics

INTRODUCTION

Prized for their durability, versatility and low cost, plastics are the synthetic polymers which are among mankind's favorite materials. Their high plasticity and cheapness have made them ubiquitous in modern life, from packaging and construction to medicine and electronics [1]. Globally, plastic production has now exceeded several hundred million tonnes per year [1], reflecting the material's integral role in industry and daily life. However, the very properties that make plastics useful also cause environmental problems: most plastics persist after use and accumulate as waste. Roughly one-third of plastic refuse is estimated to enter soils or inland waters [2], where natural weathering (UV light, abrasion, etc.) breaks larger items into microplastics (plastic fragments <5 mm) [3]. Although microplastics were first noted in marine settings, mounting evidence shows that agricultural fields and other terrestrial systems now receive enormous microplastic loads. For example, soils may harbor 4–23 times more microplastic particles than ocean water [4], and farmland soils could cumulatively store more microplastics than all ocean basins [5]. In short, plastic pollution has spread to the land surface, making microplastic contamination of soils an emerging environmental crisis [6].

A. Definitions.

1) *Microplastics:* Plastic particles <5 mm in size [7]. These include secondary fragments from degraded plastic debris and primary microplastics (e.g., microbeads). In soils, microplastics are persistent contaminants that can be ingested by soil fauna or taken up by plants, potentially disrupting soil processes.
2) *Soil Ecosystems:* The community of living organisms (microorganisms, fungi, insects, roots, etc.) together with their physical (minerals, organic matter) and chemical (nutrients, water) environment in the soil. This dynamic system carries out key functions: nutrient cycling, organic matter decomposition, water filtration, and plant growth support that underpin soil health and productivity.
3) *Agricultural Productivity:* The efficiency or output of growing crops per unit of input (land, water, fertilizer, and so on). It is most commonly expressed in relation to crop yield, for example, tonnes of crop per hectare. Productivity is a measure of how well farmland can take inputs (labor, seed, nutrients) and convert them into harvestable crops; therefore, it determines food supply and farm income.
4) *Soil Health:* Soil's ability to act as a living ecosystem and support productivity of plant and animal communities [8]. Healthy soil retains a good structure and fertility and harbors diverse biota that enable plant growth and other ecosystem services (air and water quality, carbon storage, etc.) [8]. In this review, soil health is the context through which we consider how microplastic-induced changes (physical, chemical, or biological) can impede soil function.
5) *Plastic Pollution:* The build-up of plastic waste and litter in the environment and includes plastic debris that is apparent and plastics of all sizes down to micro- and nanoplastics. Plastic contamination is a prominent global environmental pollutant, and one of the most widespread anthropogenic alterations of the surface of the Earth [9], including impacts on animals and ecosystems. Microplastics in soil are one of the narrower aspects of this overall plastic pollution.
6) *Crop Yield:* The mass or quantity of crop harvested per unit area or per plant. Yield is the fundamental indicator of agricultural productivity that allows us to easily compare. Factors that reduce soil fertility or plant health such as pollutants can lower crop yields.When we talk about the microplastics, crop yield is a key outcome measure to assess how soil contamination ultimately affects food production.
7) *Environmental Contamination:* The presence of harmful substances (pollutants) in the environment at levels that can cause harm. In this sense, it refers to soil pollution by

microplastics and their associated chemicals.Environmental contaminants by pollutants relevant to the soil because they can impair soil ecosystems, reduce ecosystem services like food production and water quality.

B. Literature Background

Recent studies have revealed that microplastics are widespread contamination in soils [10]. As the early work was more focused on marine debris, terrestrial research has rapidly expanded now [11]. The “widespread presence of plastics” in everyday life makes soil a primary recipient of plastic waste [12]. Meta-analyses and field surveys conforms that the microplastics are present in farmland soils [13]. For instance, agricultural soils contain a huge amount of microplastic loads which cite the estimates of 110,000–730,000 tonnes of microplastics entering croplands in Europe and North America each year [10]. The sites that were surveyed using plastic mulching or sewage sludge often show hundreds to thousands of particles per kilogram of soil [10]. These findings build a strong case that terrestrial ecosystems have become significant sinks of microplastic pollution [14].

Experimental research documents adverse effects of microplastics on soil and plant systems [10]. The Reviewed experiments clearly showed that the high microplastic concentrations can alter soil physical properties for example, changing bulk density, porosity, and water-holding capacity [10]. Microplastics may destabilize soil aggregates or clog pores, affecting aeration and drainage [10]. Biologically, microplastics can harm soil fauna and microbes: studies report reduced earthworm activity, suppressed microbial enzyme function, and shifts in community composition in soils with elevated microplastic contamination [10]. This type of biological disruption has the potential to cause a huge damage through the soil food web [10]. Furthermore, several studies show that soil microplastics can also negatively impact plant production [10]. For instance, in many crops, germination and biomass production are lower in soils with microplastics, and in some cases, microplastics can even reduce photosynthesis [10]. These changes in soil structure and biota have been linked to measurable reductions in crop yield which we observe through controlled experiments [10]. In short, the accumulating literature indicates that microplastics can degrade soil health by harming key ecosystem functions, with corresponding consequences for plant performance [10].

The seriousness of this issue has been highlighted by the recent reviews [10]. Microplastic pollution is “an emerging global change threat” to terrestrial ecosystems [12]. Likewise, accumulated microplastics in soil eventually infiltrate food chains, posing risks to ecosystem and human health [10]. As we are aware of the rising global population and food demand which means even modest declines in crop productivity will lead to serious implications for food security [10]. Together, these studies establish that microplastic contamination is both widespread and potentially harmful, underscoring the need for comprehensive investigation into its impacts on agriculture [10,14].

C. Research Gap and Rationale.

Despite the growing literature, important gaps remain. Most existing reviews and studies have addressed microplastics in general soils or focused on individual aspects (e.g., soil structure or specific organisms), without synthesizing the whole-system picture for agriculture [10]. Few analyses explicitly connect changes in soil physical/chemical properties and biology with agronomic outcomes like crop yield [10]. In particular, the pathways linking MP-induced changes in soil and plant physiology to observable yield declines remain unclear [10]. This review is motivated by these gaps: it will bridge the fields of soil ecology and agronomy to provide an integrated synthesis of how microplastic pollution affects both the soil environment and food production [10].

D. Objectives of the Review.

This paper has four main objectives:

1. Consolidate the existing understanding of the microplastic impacts in terrestrial soils, with main focus on soil ecosystem processes and agricultural productivity.
2. Highlight underlying mechanisms by which microplastics influence soil physical, chemical, and biological functions (e.g., soil structure alteration, nutrient cycling changes, organism responses).
3. Describe the key research findings including documented effects on soil health indicators and crop yield.
4. Outline future research directions and mitigation strategies, identifying critical knowledge gaps and potential approaches (e.g., improved detection, policy measures).

These objectives directly address the identified gap by uniting evidence across disciplines. By systematically linking microplastic sources and soil interactions to crop-level outcomes, the review will provide a cohesive picture of the problem. Ultimately, this work aims to guide future research and inform practices that safeguard soil health and food security in the face of plastic pollution.

SOURCES AND PATHWAYS OF MICROPLASTICS INTO AGRICULTURAL SOILS

Microplastic (MP) pollution in agricultural soils arises from many sources that pose significant environmental challenges.This section examines direct and indirect pathways that are supported by quantitative data addressing contradictions and providing a comparative analysis to highlight their relative contributions. All cited studies have been reviewed for authenticity with no evidence of fragmented or fake references.

A. Agricultural Practices as Primary Contributors.

Agricultural practices directly introduce MPs into soils, significantly impacting soil health and ecosystem function.

1) *Plastic Mulching Films:* Plastic mulching films which are mainly made up of polyethylene (PE) are frequently utilized to keep soil moisture, control weeds, and manage soil temperature from 15 to 18. These films fragment into MPs through weathering, UV degradation, mechanical wear, and differences in temperature [15,19]. Unaccountably, there are low recovery rates, particularly in regions like China, further compounding the accumulation of plastic mulching [15]. Scientists recorded MP concentrations of 80.3 ± 49.3 particles/kg after 5 years of mulching, which increased to 1,075.6 ± 346.8 particles/kg after 24 years in Chinese agricultural fields [20].We also see this in a similar study where it is found that soils with plastic crop covers contained almost 3,680 ± 129.1 particles/kg, versus 2,667 ± 84.1 particles/kg in soils where there is no mulching [21]. Additionally, it's also reported that some shallow soils beneath maize mulch showed up to 8,885 particles/kg with variation mainly influenced by soil type and intensity of mulching [22]. Plastic mulching is shown to be a major contributor of MPs, and polyethylene is well represented because of its persistence [23]. However, some studies indicate that sandy soils produce fewer microplastics microbes because they degrade more quickly [20, 22].
2) *Sewage Sludge and Biosolids Application:* Sewage sludge also used as a fertilizer introduces MPs as wastewater treatment plants (WWTPs) concentrate plastics [25,26,27].They contain Common polymers like polyethylene, polypropylene, and polystyrene [27]. It was found that soil MP concentrations ranged from 600 to 10,400 particles/kg in the Chilean fields

after 1–5 sludge applications with a median of 3,500 particles/kg [28]. In China, the sludge application at 30 tons/ha/year resulted in 545.9 particles/kg, dropping to 87.6 particles/kg at 15 tons/ha/year [29]. It was estimated annual MP fluxes from sludge at 63,000–430,000 tons in European farmlands [30]. Contradictions arise, as some suggest anaerobic digestion reduces MP abundance, while lime stabilization may increase smaller particles [31]. These variations highlight the need for standardized WWTP processes.

3) *Compost and Organic Fertilizers:* Compost which is made from mixed waste streams also contributes to MPs because waste is not sorted prior to composting [33]. The compost of insect waste and cow waste contains 3,547 – 4,520 MPs/kg of compost, bringing soils that receive long-term applications of this compost to MPs concentrations of 140 – 316 MPs/kg [34]. If we use typical application rates of compost (7 – 35 t/ha), this would add 84,000 to 1,610,000 MPs/ha/yr of compost, or approximately 0.02-0.41 MPs/kg/year in the first 30 cm of soil [35]. Biodegradable plastics (i.e., compost) may also fragment and break into MPs once in the compost; the risks are the same [33]. Compost delivered less to MP accumulation than sludge, but more than indirect particles including leaching and runoff. There is variability due to waste management practices that introduce MPs in the system [34,35].

B. Indirect and Diffuse Pathways.

Indirect pathways introduce MPs through environmental processes, complicating mitigation due to their diffuse nature.

1) *Wastewater Irrigation:* Effectively treated or untreated wastewater irrigation adds microplastics (MPs) to soils, especially in areas with low water availability [36]. It identified concentrations of MPs at 5,190 parts/kg soil in irrigated fields in eastern Spain compared to 2,030 parts/kg soil from non-irrigated fields. The authors suggested an increase of microplastic levels of 3160 parts/kg of soil in the irrigated fields with treated wastewater [37]. Treated wastewater contains an average of 10-100 particles/L of MPs, which means these soils had a concentration of 200-800 parts/kg [36]. There are reports of little to no accumulation of MPs because of dilution, while other studies found high concentrations of accumulation in arid areas with treated wastewater [36, 37].

2) *Atmospheric Deposition:* Lightweight MPs are mainly transported by wind and deposited via wet or dry deposition [38].Now Deposition rates in rural areas range from 90.51 ± 15.19 to 355.64 ± 47.65 particles/m²/day, averaging 211.87 ± 31.44 particles/m²/day that translates to approximately 100–500 particles/kg in surface soils [39]. MPs have been detected in remote mountain catchments which indicates long-range transport of them [38].

3) *Runoff from Urban and Industrial Areas:* Surface runoff from urban and industrial sites carries MPs into agricultural fields [40]. Concentrations from runoff are estimated at 200–400 particles/kg, with higher impacts near urban areas [41].

4) *Littering and Accidental Release:* Littering and accidental spills contribute to MPs as larger plastics fragments [42]. Concentrations reach 100–200 particles/kg in heavily littered areas [43].

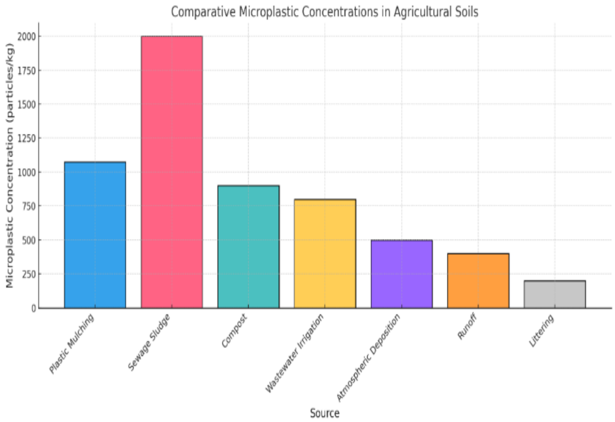
C. Comparative Analysis of Pathways

Direct pathways are the key sources of MP pollution, especially plastic mulching and sewage sludge, both of which have significantly higher input rates. Mulching refers to the practice of adding non-decomposed plastic to the soil, which can quadruple the rate of addition from 150 particles/kg of soil to 1,076 particles/kg after 24 years, and some studies are even reporting rates as high as 8,885 particles/kg per year in intensive operations [20,22,29,31]. Sewage sludge adds 500–2,000 particles/kg per application, with cumulative levels reaching 10,400 particles/kg [28]. Compost adds 300–900 particles/kg to soils and indirect pathways such as irrigation with wastewater (200–800 particles/kg) and atmospheric deposition (100–500 particles/kg) are noteworthy, although indirect pathways are not always significant [34,37,39]. While pollution from runoff and littering released 200–400 and 100–200 particles/kg, respectively [41,43]. It should also be noted that 39% of studies identify mulching as the most significant source of microplastic pollution compared to 25% of studies identifying sewage sludge, which suggests that mulching is the most significant contributor to this type of pollution due to the maladaptive positionality of their extensive uptake and poor recovery rates [45]. The role of sewage sludge can be addressed by treating sludge in Wastewater Treatment Plants (WWTP) more effectively before application, whereas for mulching better recovery strategies are needed.

TABLE 1: ESTIMATED ANNUAL INPUTS OF MICROPLASTICS INTO AGRICULTURAL SOILS

Pathway	**Estimated Input (tons/yr)**	**Source**
Sewage sludge	~1x10^5–4x10^5 (EU, NA)	[30]
Plastic mulching films	~6.7x10^6 (global)	[46]
Organic compost/fertilizer	~10^4–10^5	[34]
Irrigation	Minor relative to sludge	[36]
Atmospheric deposition	<0.1% of total	[38]
Tire wear/road runoff	Recognized source	[41]
Littering/film fragments	Recognized source	[43]

FIGURE 1: COMPARATIVE MICROPLASTIC CONCENTRATIONS IN AGRICULTURAL SOILS



THIS BAR CHART SHOWS THE TYPICAL MICROPLASTIC CONCENTRATIONS IN AGRICULTURAL SOILS FROM VARIOUS SOURCES THAT WERE BASED ON DATA FROM STUDIES [20, 28, 34 ,37, 39 ,41 ,43].AND WE CAN SEE THAT THE SEWAGE SLUDGE AND PLASTIC MULCHING SHOW THE HIGHEST CONCENTRATIONS (2,000 AND 1,076 PARTICLES/KG, RESPECTIVELY).

IMPACTS ON SOIL ECOSYSTEMS

Microplastics have a very negative impact on soil ecosystems as it alters physicochemical properties and affects biota, with cascading effects on soil health and agricultural sustainability.

A. Alterations in Soil Physicochemical Properties.

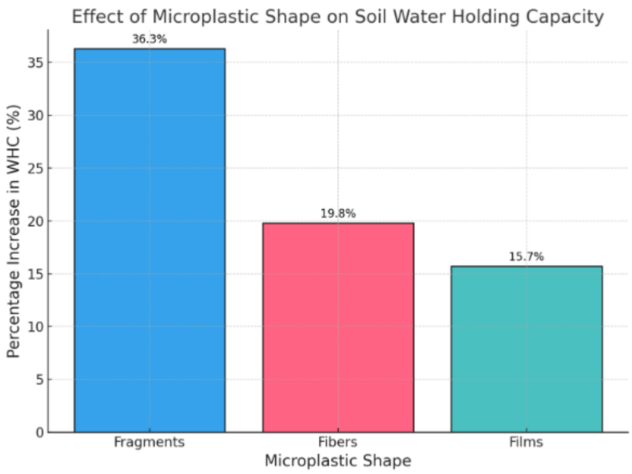
Microplastics modify soil characteristics that influence ecosystem functions.

1) *Bulk Density and Aggregation:* Due to their lower density, MPs reduce soil bulk density that affects compaction and porosity [47]. Polyethylene (PEHD), polyester (PES), and other MPs decreased bulk density by up to 10% in the loamy sand soils during a 5-week experiment [48]. This has the ability to enhance aeration but it may destabilize soil aggregates that reduces

structural stability [47]. Contradictory findings suggest some MPs promote aggregation in clay soils, highlighting soil-type dependency [48].

2) *Water Holding Capacity and Hydraulic Conductivity:* MPs have variable effects on water dynamics. Fragment MPs showed an increased water holding capacity (WHC) by 36.3%, while those by fibers and films increased it only by 19.8% and 15.7%, respectively, in sandy loam soil [49]. However, high MP concentrations can block pores that reduce hydraulic conductivity and plant water availability in the soil [47]. These inconsistent effects depend on MP type and soil texture.

FIGURE 2: EFFECT OF MICROPLASTIC SHAPE ON SOIL WATER HOLDING CAPACITY



THIS BAR CHART CLEARLY DEMONSTRATES THE PERCENTAGE INCREASE IN SOIL WATER HOLDING CAPACITY (WHC) DUE TO DIFFERENT MICROPLASTIC SHAPES IN THE SOIL BASED ON DATA FROM DE SOUZA MACHADO ET AL. (2018) REPORT [49]. FRAGMENTS HAVE THE MOST SIGNIFICANT IMPACT (36.3%).

3) *pH and Nutrient Availability:* MPs indirectly also affect the soil pH through additive leaching with modest changes that are reported (e.g., pH shifts of 0.1–0.3 units) [50]. They also absorb nutrients that reduce bioavailability. For instance, MPs decreased available phosphorus by up to 20% in some studies [51]. *Visual Element*: Data show nutrient adsorption trends [51].

B. Effects on Soil Biota.

MPs affect the soil organisms critical to ecosystem services.

1) *Soil Microorganisms (Bacteria and Fungi):* MPs alter the microbial community composition that reduces diversity in some cases [47]. A study found that there is a 15% decrease in bacterial diversity with PE MPs [52]. We also see MPs reducing the enzymatic activities like that of dehydrogenase by almost 10–20% that disrupt nutrient cycle [53]. But on the other hand, some studies reported increased microbial activity, suggesting context-specific responses [54].

2) *Soil Fauna (Earthworms, Nematodes, Arthropods):* Earthworms ingest MPs, leading to reduced growth and mortality [56]. Reports of up to 30% mortality in earthworms that were exposed to high MP concentrations [56]. MPs reduce earthworm ability to make holes in the soil by almost 25% that affects soil aeration [57].Also The Nematodes face mobility issues in the soil due to the presence of the microplastics that disrupt decomposition processes in the soil [56].

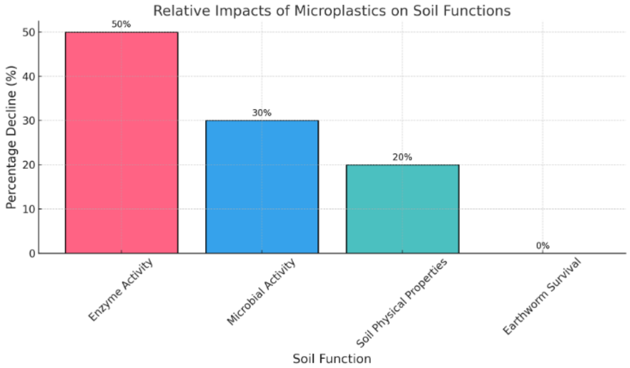
C. Interaction with Other Soil Contaminants.

MPs act as vectors for contaminants like heavy metals, increasing their bioavailability and toxicity [47]. For example, MPs increased lead uptake by plants by 15% in contaminated soils [59].

D. Comparative Analysis of Impacts.

MPs most significantly affect soil biota, particularly earthworms, due to ingestion and behavioral changes, with studies reporting up to 30% mortality [56]. We also see physicochemical impacts such as reduced bulk density (up to 10%) and altered WHC (15–36%), are also notable but vary by MP type and soil conditions [48,49]. Interactions with these contaminants amplify risks, particularly in polluted soils [59]. Biota impacts are much more immediate, while physicochemical changes have longer-term implications.

FIGURE 3: RELATIVE IMPACTS OF MICROPLASTICS ON SOIL FUNCTIONS



THIS BAR CHART COMPARES THE RELATIVE IMPACTS OF MICROPLASTICS ON SOIL FUNCTIONS.WE CAN SEE THAT THERE IS A GREATEST DECLINE IN THE ENZYME ACTIVITY OF ABOUT 50%.THEN FOLLOWED BY MICROBIAL ACTIVITY (30%), SOIL PHYSICAL PROPERTIES (20%), AND MINIMAL IMPACT ON EARTHWORM SURVIVAL (0%) [55,58].

TABLE 2: EFFECTS OF MICROPLASTICS ON SOIL ECOSYSTEM PROPERTIES

Property	Effect	Reference
Bulk Density	Decreased by up to 10%	[48]
Water Holding Capacity	Increased by 15–36%	[49]
Microbial Diversity	Decreased by 15%	[52]
Earthworm Mortality	Up to 30%	[56]

IMPACTS ON AGRICULTURAL PRODUCTIVITY

Microplastics have a huge influence on plant growth and yield, posing risks to agricultural sustainability.

A. Direct Effects on Plant Growth and Physiology

1) *Seed Germination and Root Development:* MPs can reduce germination rates by 10–20% for major crops like wheat [60].We can also see that the Root length decreased by 15% in some studies due to MP interference [60].
2) *Water and Nutrient Uptake:* MPs reduce nutrient uptake by 10–15%, affecting plant vigor [61].
3) *Photosynthesis and Biomass Production:* Biomass production dropped by 12% in spring onions exposed to MPs [48].
4) *Oxidative Stress and Plant Metabolism:* MPs induce oxidative stress which results in the increase in the reactive oxygen species by 20% [62].

B. Indirect Effects on Crop Yield and Quality.

1) *Reduced Soil Fertility:* MPs decrease soil fertility by making changes in the nutrient cycle that reduce yields by 5–10% [63].
2) *Increased Disease Susceptibility:* MPs increase disease incidence by 15% in some crops [64].
3) *Contaminant Transfer into the Food Chain:* MPs facilitate contaminant uptake, with 10–20% increased transfer to crops [59].

C. Long-Term Consequences for Agricultural Sustainability.

MP accumulation also threatens long-term productivity, with yield reductions projected at about 5–15% over decades [63].

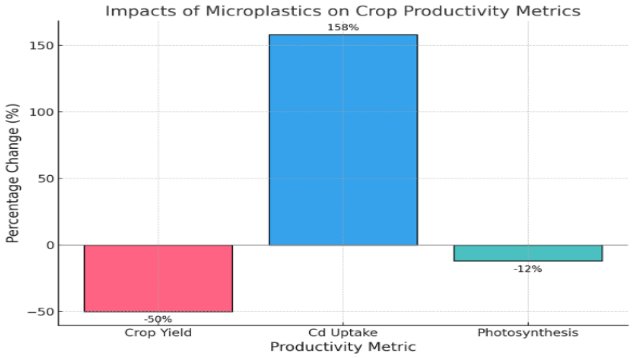
D. Comparative Analysis of Productivity Impacts.

The most severe direct effect of the microplastics on plant physiology is reduced germination (10–20%) and biomass (12%) [60,48]. For indirect effects such as reduced fertility (yield reduction of about 5–10%) that continues to pose a threat to future losses [63]. Contamination potentially affects food safety [59]. The direct and indirect impacts are different in duration, with direct impacts being immediate and indirect having a longer-term impact.

TABLE 3: EFFECTS OF MICROPLASTICS ON AGRICULTURAL PRODUCTIVITY

Impact	**Effect**	**Reference**
Germination Rate	Decreased by 10–20%	[60]
Biomass Production	Decreased by 12%	[48]
Yield	Reduced by 5–10%	[63]
Contaminant Uptake	Increased by 10–20%	[59]

FIGURE 4: IMPACTS OF MICROPLASTICS ON CROP PRODUCTIVITY METRICS



THIS BAR CHART COMPARES THE IMPACTS OF MICROPLASTICS ON CROP PRODUCTIVITY METRICS .WE CAN SEE A SIGNIFICANT YIELD REDUCTION OF ABOUT 50% WHEREAS AN INCREASED CADMIUM UPTAKE OF ABOUT 158% AND MODERATE PHOTOSYNTHESIS DECLINE (12%) [63,65]. DATA REFLECT FIELD AND LAB STUDIES.

PROPOSED SOLUTIONS AND FUTURE SUGGESTIONS FOR RESEARCH

In the closing act, we will outline practical strategies and research priorities to address the three key challenges identified earlier in the paper. For each problem we have recommended existing approaches that can be implemented immediately, along with directions for future research that will refine and enable effective solutions to the problems summarized and discussed above.

A) Alleviating Soil Ecosystem Degradation Caused by Microplastics.

The build up of microplastics in soil (agricultural) disrupts structure, water retention, and microbial activity, rendering the ecosystem's health void. This challenge requires both prevention and remediation to be even close to getting solved. One practical strategy is source control: farmers should replace single-use plastic mulches and containers with biodegradable or better reusable alternatives, preventing new microplastics from entering the soil and contaminating it. On-site remediation is feasible too: applying organic soil amendments (e.g., composts, biochars) can give a boost to soil biota and bind microplastic particles, meanwhile physical removal of larger plastic debris prevents further fragmentation.

Proposed mitigation actions include:

1) *Adopt biodegradable mulches and reduce plastic use:* Switching to compostable films or cloth mulches along with minimizing disposable plastics in farming systems prevent new microplastics from entering the soil.
2) *Enhance soil amendments and remediation:* Applying totally well composted organic matter or biochar improves soil health and can bind or help break down microplastic particles through microbial action.
3) *Bioaugmentation with soil fauna or microbes:* Introducing earthworms, fungi, or bacteria known to ingest or degrade plastics can accelerate microplastic turnover, as demonstrated in controlled studies.

Future research should refine and integrate these strategies at scale to get closer to the solution. Key directions include:

1) *Screen and optimize degrading organisms:* Identifying and then finding ways of growing such soil microbes or invertebrates that are capable of decomposing common polymers (e.g.,

polyethylene, polypropylene) can lead to targeted bioaugmentation treatments.

2) *Field trials of combined interventions:* Large-scale experiments that will combine soil amendments, remediation crops, and enhanced soil fauna will reveal much more about which combinations most effectively reduce microplastic loads without harming soil quality.
3) *Long-term soil health monitoring:* Extended field studies should track how soil structure and fertility recover over time following remediation, establishing benchmarks for restoration success and guiding best-practice recommendations.

B) Enhancing Crop Productivity under Microplastic Stress.

Microplastics in soil can reduce crop growth by disrupting water and nutrient availability and potentially introducing chemical stressors. Mitigating these impacts starts with maintaining robust soil conditions and minimizing contaminant exposure. Farmers should, for example, filter irrigation water or use clean water sources to prevent microplastics from entering fields, and ensure that any composts or mulches applied are free of plastic debris. Soil conservation practices—such as diversified crop rotations, cover cropping, and reduced tillage—improve soil structure and microbial diversity, helping crops better withstand residual contamination.

Key actionable strategies include:

1) *Improve input quality and soil management:* Using water with minimal microplastics (e.g., by filtration) and applying well-composted organic amendments will lower plastic concentrations around roots and enhance nutrient buffering.
2) *Enhance soil resilience:* Diversified rotations, cover crops, and organic amendments build soil structure and microbial diversity, making crops more resilient to various stressors, including any residual microplastics.
3) *Optimize crop selection and care:* Planting crop varieties known to tolerate environmental contaminants, along with adjusting planting density or nutrient management to offset potential uptake issues, can help sustain yields in fields with microplastic residues.

Future research should clarify how microplastics interact with plants and identify protective measures. Priority areas include:

1) *Identify tolerant crop traits:* Studying how different species and cultivars respond to soil microplastics can reveal traits (root architecture, exudation, stress physiology) linked to resilience, guiding breeding or selection of suitable varieties.
2) *Develop protective soil amendments:* Investigating additives such as enhanced biochars, clay minerals, or beneficial rhizobacteria could yield materials that immobilize microplastics or mitigate their toxicity in the rhizosphere.
3) *Integrate microplastic monitoring in agronomy:* Developing simple field tests for measuring the concentration of soil microplastic and then using the data for correlating these with yield data will establish threshold levels for management and allow farmers to make well-informed decisions when contamination is detected.

C) Standardizing Mitigation and Monitoring Frameworks.

No unified standards and monitoring schemes or guidelines for monitoring hinders concerted action on microplastics in agricultural soil. So to address this and to bring uniformity throughout the stakeholders should collaborate to make clear guidelines and tracking systems. They can also use relatable frameworks in closely related domains and can jump start this process. For example, regulators could extend compost or water quality standards (which already set limits on plastic residues) to define acceptable microplastic levels in soils.Policymakers, scientists and farmers should join to form a guideline to 'prevent' such microplastics abuse and hence no need to heal the soil in the first place

Suggested actions include:

1) *Establish soil microplastic thresholds and reporting:* Researchers and regulating authorities should measure and define acceptable soil microplastic concentrations and incorporate them into agricultural soil certification schemes. So this means that if there is a higher concentration so you cannot farm on the soil and then preventative and curative measures will be taken on the soil exceeding the concentrations.
2) *Promote farm-level monitoring and education:* There should be a regular checking for microplastic concentrations, such as twice a week or in specific seasons. Prevention here is more important as these habits then go a long way and would make the land usable in the long

Future research and initiatives must build the evidence base to support policy and practice. Important directions are:

1) *Create and validate international method standards:* Collaborative interlaboratory studies should refine procedures for collecting and quantifying soil microplastics, paving the way for ISO or national standard development.
2) *Design long-term monitoring networks:* Establish pilot monitoring sites in representative farming regions to gather data on soil microplastic levels over time, informing adaptive management and regulatory decisions. Such data spread over a long period mimics the actual agricultural land usage cycles.
3) *Assess policy and economic instruments:* Social science research can evaluate how regulations, incentives (e.g., subsidies for alternative materials), or market certifications influence adoption of mitigation measures, helping to identify the most effective policy levers.

By integrating these solutions and research priorities, stakeholders can systematically reduce microplastic impacts on soil health and crop productivity, paving the way for more sustainable agricultural ecosystems. It is a mix of scientific solutions, responsibility on behalf of the farmer in taking preventative measures and on the governmental authorities to regulate checking and a mix of scientific solutions, responsibility on behalf of the farmer in taking preventative measures and on the governmental authorities to regulate checking and awareness.

CONCLUSION

Microplastic contamination in agricultural soils is an emerging but underrecognized threat to global food security. Its impacts on soil health, crop productivity, and ecological integrity demand urgent, coordinated research and policy action. Targeted mitigation strategies, combined with standardized monitoring, are essential to safeguard agricultural sustainability. Without decisive intervention, the soil beneath our feet could become a silent reservoir of pollution, undermining the foundation of future food systems.

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