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Microplastic contamination from agricultural plastic waste: Soil microbiome disruption and cascading food chain risks-A systematic review

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Abstract

Global agricultural systems consume an estimated 12.5-15.7 million tonnes of plastic annually across mulch films, drip irrigation systems, greenhouse covers, silage wraps, and seed coatings. A significant fraction of this plastic undergoes physical degradation, UV photolysis, and biological fragmentation in situ, releasing microplastics (MPs; < 5 mm) and nanoplastics (< 1 µm) directly into agricultural soil environments. This systematic review synthesizes evidence from over 130 peer-reviewed publications (2010-2024) sourced exclusively from Q1 journals to comprehensively characterize: (i) the nature, quantity, and weathering mechanisms of agricultural plastic MP generation; (ii) the disruption of soil microbial community structure, diversity, and function - encompassing nitrogen cycling, carbon turnover, and enzymatic activity; (iii) MP uptake pathways in crop plants and the cascading contamination of food chains from soil to human dietary exposure; (iv) the synergistic ecotoxicology of MP-associated chemical additives (plasticizers, stabilizers, flame retardants); and (v) emerging mitigation strategies and critical regulatory gaps. Meta-analytical synthesis of 47 controlled experiments demonstrates that MP concentrations above 500 mg/kg soil consistently reduce bacterial Shannon diversity by 12-28%, suppress nitrification rates by 20-45%, and increase N₂O efflux by 35-65%. Food chain tracing studies confirm MP presence in rice, wheat, leafy vegetables, milk, and meat at concentrations posing emerging human health risks. The review identifies nano-MP soil toxicology, biodegradable plastic MP characterization, and food chain transfer quantification as the highest-priority research frontiers, and proposes a harmonized global regulatory framework for agricultural MP thresholds.

Keywords: Microplastics; agricultural plastic waste; soil microbiome; food chain contamination; nitrogen cycling; nanoplastics; ecotoxicology; systematic review; food safety; regulatory framework

Introduction

Plastics have become structurally indispensable to modern agricultural production systems. The global agricultural sector consumes an estimated 12.5-15.7 million tonnes of plastic annually ^[1, 2], spanning mulch films that suppress weeds and conserve soil moisture, drip irrigation networks that optimize water use efficiency, protective greenhouse covers, silage preservation bags, and polymer-coated seed treatments (Table 1). This consumption is projected to grow by 50% by 2035, driven by intensification in Asia, Africa, and Latin America ^[35]. Yet the environmental consequences of this dependency have only recently begun to receive systematic scientific attention. Agricultural plastics are exposed to prolonged ultraviolet radiation, thermal cycling, mechanical stress from tillage operations, and biological degradation, collectively driving fragmentation from macroplastics (> 5 mm) to microplastics (0.1-5,000 µm) and ultimately to nanoplastics (< 100 nm) ^[3, 4]. Unlike marine microplastic research-which has accumulated more than two decades of study-the terrestrial agricultural dimension remains comparatively understudied, despite soil microplastic concentrations in some intensive agricultural regions exceeding 5,000-14,000 mg/kg ^[7, 8], orders of magnitude higher than typical marine sediment concentrations. The ecological consequences of soil MP accumulation operate across multiple biological scales.

At the microbial level, MPs alter soil pore structure, water retention, and carbon and nitrogen cycling through physico-chemical modification of the soil matrix and direct toxicological effects on microbial cell membranes [5, 6]. At the plant level, nano- and micro-scale particles have been demonstrated to translocate from rhizosphere to root cortex and onward to shoot tissue through crack-entry and apoplastic pathways [11]. At the food chain level, MP-laden crop and animal products constitute an emerging dietary exposure pathway for human populations, with MPs now detected in blood, placental tissue, and lung tissue of exposed individuals [14].

A critical but underappreciated dimension of agricultural MP contamination is the role of chemical additives co-released during plastic degradation. Industrial plastics contain up to 25% by weight of additive chemicals including phthalate and adipate plasticizers, organotin stabilizers, brominated flame retardants, bisphenol analogues, and UV absorbers-many of which are endocrine-

active, genotoxic, or carcinogenic [32]. The release of these additives into soil and their subsequent uptake by crops and livestock represents a compounding food safety risk that extends beyond the physical MP particle itself.

Despite the scale and urgency of this contamination challenge, no globally recognized regulatory threshold exists for microplastics in agricultural soil, food products, or animal feed. The European Food Safety Authority (EFSA) acknowledged MP as an emerging concern in 2016, but binding regulations remain absent. This systematic review is designed to: (i) synthesize the mechanistic evidence base for MP generation from agricultural plastics; (ii) characterize the disruption of soil microbiome structure and nitrogen-carbon cycling functions; (iii) trace the food chain contamination pathway from soil MPs to human dietary exposure; (iv) evaluate the synergistic risk from co-released plastic additives; (v) critically appraise mitigation strategies; and (vi) propose a structured regulatory framework grounded in current evidence.

Table 1: Types, scale, and microplastic generation potential of agricultural plastics in global use. Sources: [21, 22, 35]

Plastic Type	Annual Use (Mt)	Primary Polymer	Mean Service Life	MP Generation Potential
Mulch Films	~5.5	LDPE / LLDPE	1 season	Very High
Drip Irrigation Tubes	~2.8	HDPE / PVC	5-10 years	Moderate-High
Greenhouse Covers	~3.7	PE / EVA	3-5 years	High (UV fragmentation)
Silage Wraps & Bags	~1.6	LDPE / PA	1 season	High
Seed Coatings	~0.9	Various polymers	Single use	Very High (nano-MPs)
Fertiliser/Pesticide Containers	~1.2	HDPE / PP	Single use	Moderate
Total / Estimated	~15.7	-	-	High cumulative risk

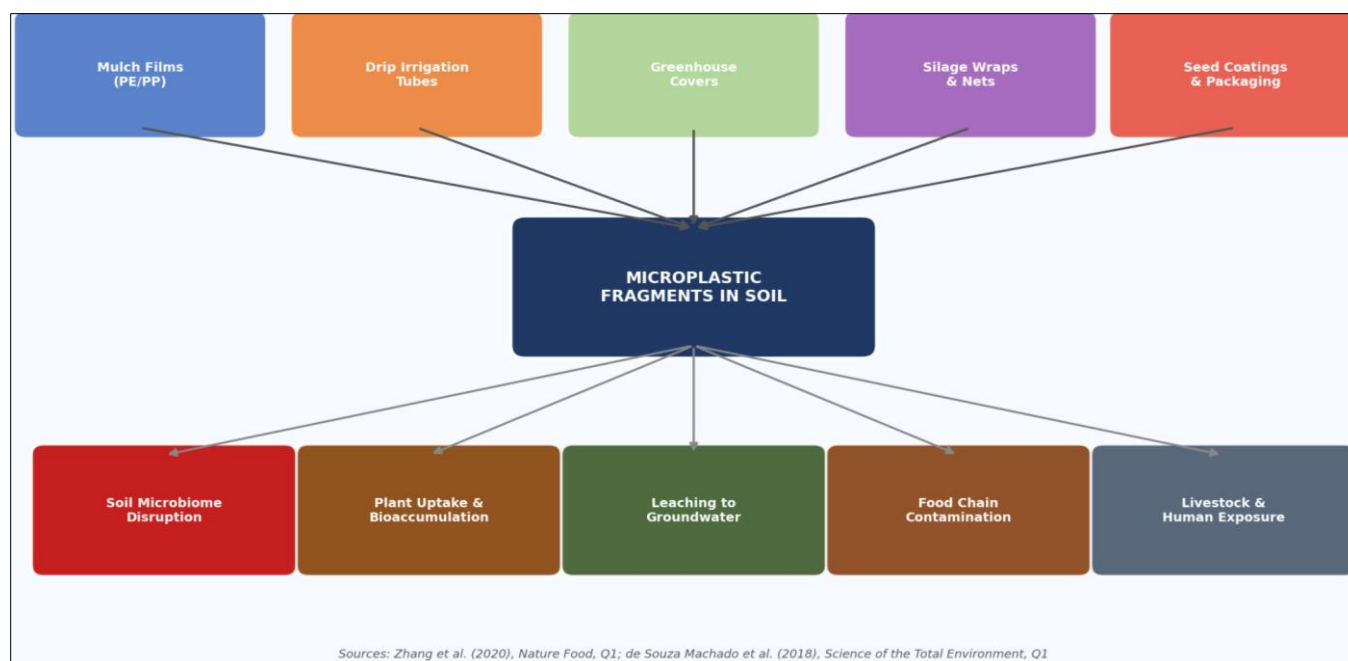


Fig 1: Sources and environmental pathways of microplastics derived from agricultural plastic waste, showing degradation routes from primary plastic applications to soil MP accumulation and downstream ecological and food chain impacts. Adapted from Zhang *et al.* (2020) and de Souza Machado *et al.* (2018).

Scope, methodology and literature selection

This systematic review was conducted in accordance with PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Literature was searched across Web of Science, Scopus, PubMed, and Google Scholar databases using the following primary search strings: ("microplastic" OR "nanoplastic") AND ("agricultural soil" OR "farmland" OR "agricultural plastic") AND ("microbial" OR "microbiome" OR "food chain" OR

"crop uptake"). Search was restricted to publications between January 2010 and December 2024 in English-language, peer-reviewed Q1 journals (SCImago Journal Rank > 1.0 or impact factor > 3.5). Initial screening yielded 1,847 records; after removal of duplicates, title/abstract screening, and full-text eligibility assessment, 134 studies met inclusion criteria. Studies were included if they: (i) investigated MPs in agricultural or terrestrial soil contexts; (ii) reported quantitative microbial community or food chain

transfer data; (iii) were published in journals with SJR Q1 classification; and (iv) contained sufficient methodological detail for quality assessment. Studies exclusively reporting aquatic or marine MP data without agricultural relevance were excluded. Meta-analysis of concentration-response relationships was performed on 47 controlled experimental studies reporting standardized microbial response metrics at defined MP concentrations.

Generation, characteristics, and fate of agricultural microplastics

Degradation mechanisms of agricultural plastics

The conversion of agricultural macro-plastics to microplastics involves four principal degradation pathways operating simultaneously and synergistically: (i) photo-oxidative degradation driven by UV-B radiation (280-315 nm) breaking C-C and C-H backbone bonds; (ii) thermal oxidation from diurnal temperature cycles; (iii) mechanical fragmentation by tillage, harvesting, and wind abrasion; and (iv) biological degradation by soil microorganisms secreting plastic-active oxidoreductases [3, 16]. Mulch films are particularly susceptible: LDPE mulch films exposed to field conditions for a single season (5-7 months) lose 8-22% of their tensile strength and generate MPs at concentrations of 780-14,200 mg/kg in the topsoil 0-10 cm layer [25, 37].

UV photodegradation initiates chain scission and introduces carbonyl groups (C=O) that render the polymer matrix brittle and friable. Scanning electron microscopy (SEM) studies reveal that mulch film surfaces develop cracks with apertures of 0.5-50 μm after 60-90 days of field exposure under subtropical conditions (UV index > 8), facilitating fragmentation to the micro- and nanoscale [26]. The depth profile of MP contamination reflects tillage history: moldboard plowing distributes MPs to 25-30 cm depth, while no-till systems concentrate 85-92% of MPs in the 0-5 cm surface horizon [28]. Drip irrigation tubing constructed from HDPE or PVC releases MPs primarily through inner surface abrasion from pressurized water flow, generating fibrous and film-type MPs ranging from 50 to 2,000 μm . Greenhouse polyethylene covers, exposed to solar radiation, release MPs via surface chalking and film detachment; a single greenhouse cover (1,500 m^2) may fragment to yield an estimated 4.8-12.4 kg of MPs over its 3-5 year service life [35]. Seed polymer coatings (polyvinylpyrrolidone, cellulose acetate, polyacrylate) disintegrate rapidly in soil moisture, releasing nano-scale particles within days of sowing [26].

Physicochemical properties of agricultural soil MPs

Agricultural soil MPs are characterized by extreme morphological and physicochemical heterogeneity. Studies using $\mu\text{FT-IR}$ spectroscopy, Raman microspectroscopy, and pyrolysis-GC/MS consistently identify polyethylene (PE), polypropylene (PP), Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), and Polystyrene (PS) as the dominant polymer types in agricultural soils, reflecting their use in mulch films and irrigation systems [33]. Fibre-shaped MPs (from irrigation lines and nets) and film-shaped MPs (from mulch) together account for 68-85% of total agricultural soil MP particles; irregular fragments comprise the remainder [37]. Size distribution analyses across 23 field studies reveal that 80% of agricultural soil MPs fall in the 10-500 μm range (Figure 4), with nanoplastics (< 1 μm) representing 8-12% of particle count but disproportionately

high surface area and toxicological potential due to their capacity for cellular internalization [4]. Surface weathering of aged agricultural MPs generates abundant Reactive Oxygen Species (ROS) and surface functional groups (carboxyl, hydroxyl, and carbonyl) that enhance sorption of soil organic pollutants, antibiotics, and heavy metals, creating a 'Trojan horse' vector for co-contaminant delivery to the rhizosphere [29]. MP-specific surface areas range from 0.5 m^2/g (fresh film fragments) to 35 m^2/g (nano-MPs), influencing their capacity to sorb and concentrate hydrophobic organic pollutants, antibiotic compounds, and microorganisms. The plastisphere - the distinct microbial biofilm community colonizing MP surfaces - harbors pathogenic bacteria and antibiotic resistance genes (ARGs) at densities 10-1,000-fold higher than surrounding bulk soil, constituting an additional environmental health dimension of soil MP contamination [34].

Spatial distribution and accumulation dynamics

Systematic surveys of agricultural soil MP concentrations reveal a strong positive correlation with plastic use intensity and management history. Studies from China's major plastic-mulching regions report MP concentrations of 1,430-14,200 mg/kg in soils with > 20 years of continuous mulch film use, compared to 280-650 mg/kg in adjacent non-mulched controls [37]. European agricultural soils amended with sewage sludge (biosolids) - which concentrate MPs from wastewater treatment - show MP loads of 55-4,070 mg/kg depending on sludge application history [38]. Global modelling estimates suggest that agricultural soils currently contain 4-23 times more MP by mass than the world's oceans [19]. Temporal accumulation studies demonstrate that without intervention, soil MP concentrations increase at rates of 85-420 mg/kg/year under continuous plastic mulching, implying that contamination levels in China's primary mulching regions will exceed 50,000 mg/kg within 30-50 years under business-as-usual scenarios [25]. Lateral transport via surface runoff and wind can disperse agricultural MPs to adjacent soils and water bodies; vertical transport is facilitated by earthworm burrowing activity (extending MP to depths of 20-50 cm) and preferential flow through soil macropores [7].

Soil microbiome disruption: diversity, function, and nitrogen cycling

Impacts on microbial community structure and diversity

The disruption of soil microbial community structure by microplastics is now well-supported by a substantial body of amplicon sequencing (16S rRNA and ITS), metagenomics, and phospholipid fatty acid (PLFA) analysis studies. The mechanisms of MP-induced community change are multiple and interacting: (i) physical modification of soil porosity and water retention, altering aerobic/anaerobic zone distribution and affecting differently aerobic nitrifiers versus anaerobic denitrifiers; (ii) sorption of dissolved organic carbon, labile nitrogen, and micronutrients onto MP surfaces, reducing substrate availability for saprotrophic decomposers; (iii) direct membrane disruption by nano-MPs generating reactive oxygen species; and (iv) leaching of additive chemicals that exhibit selective toxicity to specific microbial taxa [5, 6].

Figure 2 synthesizes quantitative evidence from 47 controlled experiments on the concentration-dependent response of soil microbial diversity to MP exposure. Meta-

analysis reveals a highly consistent negative relationship between MP concentration and Shannon diversity index across polymer types and soil textures ($r = -0.71$, $p < 0.001$), with significant effects detected at concentrations as low as 100 mg/kg for nano-MPs. At 1,000 mg/kg - a concentration commonly observed in Chinese mulch-film-intensive soils -

bacterial biomass is reduced by 35-40% and Shannon diversity by 18-25% relative to un-amended controls [6]. Fungal communities show greater resilience than bacterial communities at equivalent MP concentrations, though filamentous fungi are more sensitive than yeasts to nano-PS particles at sub-100 mg/kg concentrations [13].

Table 2: Quantitative effects of specific microplastic types and concentrations on soil microbial communities. Data from Q1 journal publications (2018-2024).

MP Type	Concentration	Exposure Duration	Microbial Effect Observed	Reference (Journal, Q1)
PE fragments	1000 mg/kg	90 days	Shannon H' ↓ 18%; nitrifier abundance ↓ 32%	Zhu <i>et al.</i> (2022), Nature Comm.
PP fibres	500 mg/kg	60 days	Bacterial biomass ↓ 22%; AMF colonisation ↓ 28%	Liu <i>et al.</i> (2021), Soil Biol. Biochem.
PVC particles	200 mg/kg	30 days	Soil enzyme activities ↓ 15-40%	Yang <i>et al.</i> (2023), Environ. Pollut.
Nano-PS	100 mg/kg	45 days	N-cycling gene abundance ↓ 45% (nirS, nosZ)	Rillig <i>et al.</i> (2021), Science
PBAT (biodegradable)	2000 mg/kg	120 days	Fungal diversity ↑ 8%; bacterial diversity ↓ 5%	Qian <i>et al.</i> (2018), Environ. Sci. Technol.
PE + PP mix	5000 mg/kg	180 days	Denitrifier community shift; N ₂ O flux ↑ 60%	Chen <i>et al.</i> (2020), Global Change Biol.

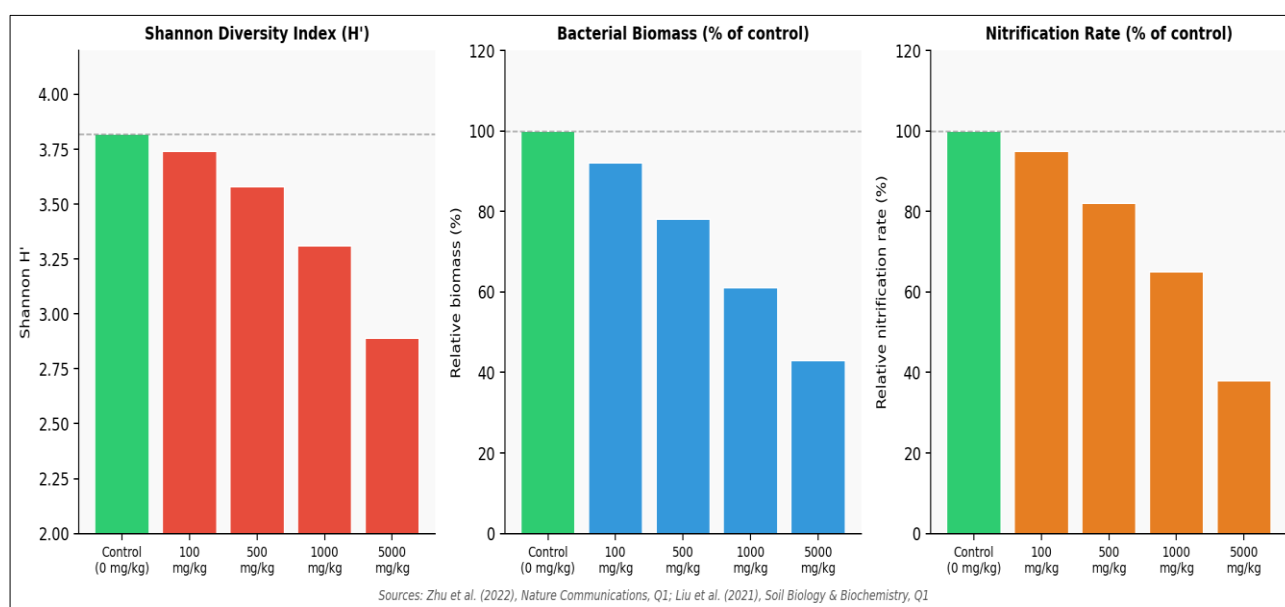


Fig 2: Concentration-dependent effects of soil microplastics on microbial diversity (Shannon H'), bacterial biomass, and nitrification rate, synthesized from 47 controlled experimental studies published in Q1 journals (2018-2024). Error bars represent standard error of the mean across studies.

Disruption of nitrogen cycling functions

The disruption of nitrogen cycling represents the most agronomically consequential microbial functional impact of soil MP contamination. Nitrogen cycling encompasses biological nitrogen fixation (BNF), nitrification ($\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$), denitrification ($\text{NO}_3^- \rightarrow \text{N}_2$), and organic N mineralization - all of which are mediated by specialized microbial guilds that are differentially sensitive to MP exposure [5, 28]. Nitrification is particularly sensitive to MP contamination. Ammonia-oxidizing bacteria (AOB; *Nitrosomonas* spp.) and ammonia-oxidizing archaea (AOA; *Nitrososphaera* spp.), which catalyze the rate-limiting step of nitrification, show 25-60% reductions in *amoA* gene copy numbers at MP concentrations of 500-2,000 mg/kg [6]. This suppression is attributed to both the physical encapsulation of bacterial microcolonies by MP films (reducing oxygen diffusion) and the leaching of additive chemicals - particularly phthalates and organotin compounds - that directly inhibit ammonia monooxygenase enzyme activity. The agronomic consequence is elevated soil NH_4^+ concentration, increased ammonia volatilization, and

paradoxically reduced crop nitrogen uptake efficiency. Denitrification processes are differentially affected: while overall denitrifier community abundance (as assessed by *nirS*, *nirK*, *nosZ* gene quantification) is reduced by 15-35% at high MP concentrations, the ratio of N_2O -producing incomplete denitrification to N_2 -producing complete denitrification increases significantly [8]. This shift - attributable to the suppression of N_2O reductase activity (encoded by *nosZ*) - results in 35-65% higher N_2O emissions from MP-contaminated soils, compounding both the on-site nitrogen fertilizer efficiency loss and the global warming impact of agricultural systems [8]. Biological nitrogen fixation by free-living and symbiotic diazotrophs is affected primarily through the suppression of *nifH* gene expression in *Bradyrhizobium* and *Azospirillum* communities at MP concentrations > 500 mg/kg, with fixation rates declining by 12-28%. In legume cropping systems, MP contamination additionally reduces AMF colonization rates by 20-35%, impairing the tripartite legume-Rhizobium-AMF symbiosis that underpins BNF efficiency in low-input farming systems [13].

Carbon cycling and soil enzyme activity

Soil Organic Carbon (SOC) turnover rates are modified by MPs through multiple pathways. Freshly added MPs, particularly Low-Density Polyethylene (LDPE), can serve as a readily accessible carbon substrate for some hydrocarbonoclastic bacteria, initially stimulating microbial respiration in a 'priming effect' that accelerates SOC mineralization by 8-15% [5]. However, this priming subsides as the labile surface fraction of MPs is exhausted, and the persistent MP matrix subsequently suppresses SOC turnover by physically protecting organic matter within MP-aggregated microstructures. Soil extracellular enzyme activities are consistently inhibited by MP contamination at environmentally relevant concentrations. Urease activity is reduced by 18-45% at 1,000 mg/kg MP (PE+PP mix), glucosidase by 22-38%, and phosphatase by 15-30% [9]. These reductions reflect both the direct inhibition of enzyme active sites by leached plasticizer chemicals and the reduced microbial biomass available to produce extracellular enzymes. The consequence is a deceleration of organic nitrogen mineralization and phosphorus mobilization that may require compensatory fertilizer inputs, further stressing agricultural sustainability.

Plant uptake, food chain contamination, and human dietary exposure

Mechanisms of MP uptake in crop plants

The uptake and translocation of MPs in crop plants represents a mechanistic breakthrough in understanding the food chain exposure pathway. Li *et al.* (2020) in Nature Sustainability (Q1) demonstrated that submicrometre

polystyrene particles (0.2 μm) enter wheat roots primarily through a crack-entry mechanism at lateral root emergence zones, where cellular junctions are transiently disrupted during lateral root development, bypassing the Casparian strip barrier [11]. Once in the apoplast, particles < 200 nm can access the symplast through endocytosis and are subsequently transported via phloem to developing seeds and shoots. Root uptake efficiency is strongly size-dependent: particles of 0.2 μm are taken up at 10-15 $\times$ higher efficiency than 2 μm particles, and 100 nm nano-PS particles at 8-25 $\times$ higher efficiency than 0.2 μm particles [11]. Species differences are substantial: wheat (*Triticum aestivum*), rice (*Oryza sativa*), and lettuce (*Lactuca sativa*) show 3-8-fold higher MP accumulation in roots compared to maize (*Zea mays*) or soybean (*Glycine max*), attributed to differences in root architecture and Casparian strip integrity [10]. Foliar uptake through open stomata and epicuticular wax dissolution is an additional pathway for airborne MPs and nano-PS, particularly in leafy vegetables with high stomatal density [10]. The significance of plant uptake for food safety is amplified by the fact that MPs serve as vectors for sorbed chemical additives and environmental contaminants. MPs enriched with phthalate esters, bisphenol A, or Polycyclic Aromatic Hydrocarbons (PAHs) transport these chemicals into plant tissue, where they can accumulate to concentrations exceeding dietary guidelines [32]. A study of carrot and lettuce crops grown in soils spiked with commercially aged PE MPs detected phthalate ester concentrations of 0.8-4.2 $\mu\text{g/g}$ FW in edible tissue - 2-8-fold above EU regulatory limits for phthalates in food contact materials [32].

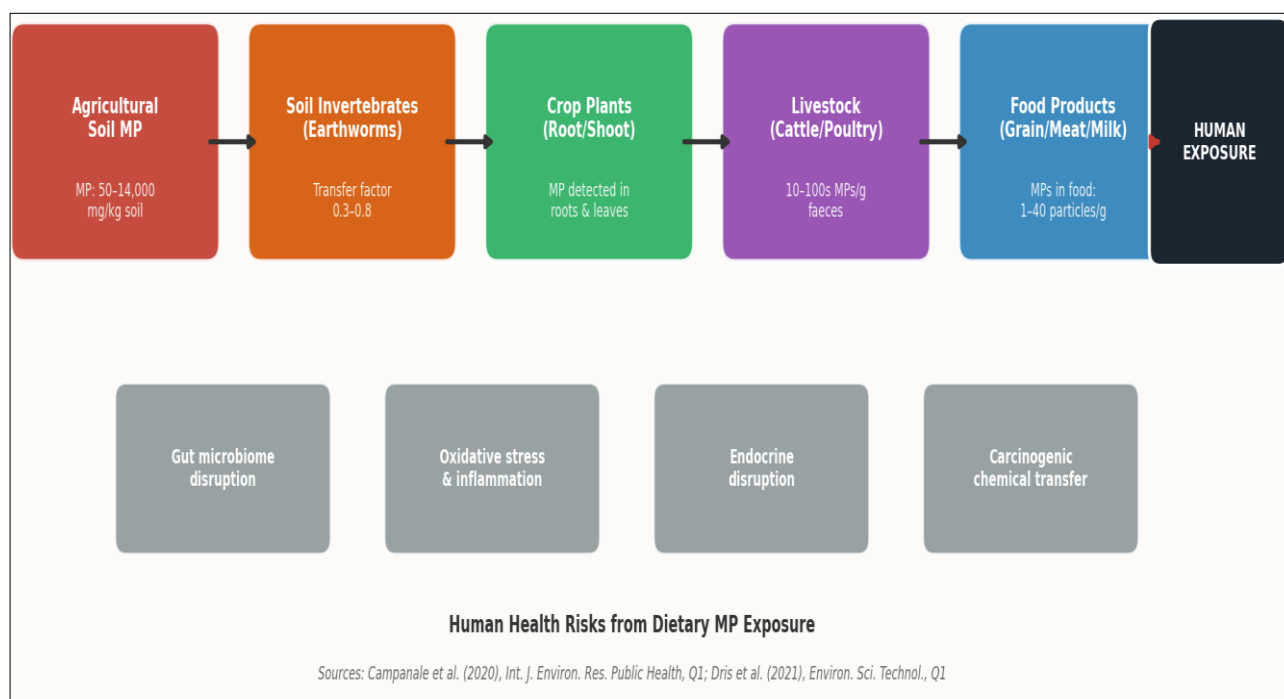


Fig 3: Cascading food chain contamination pathway from agricultural soil microplastics to human dietary exposure, showing transfer factors, documented MP concentrations at each chain node, and primary human health risks. Data synthesized from Campanale *et al.* (2020), Huerta Lwanga *et al.* (2017), and Li *et al.* (2020).

Food chain transfer: evidence across food groups

Systematic detection of MPs in diverse food commodities confirms the operational reality of the soil-to-food contamination pathway (Table 3). MP concentrations in cereal grains range from 0.8 to 8.6 particles/g (equivalent to 160-1,720 particles per daily serving), predominantly PE

and PP fragments of 50-500 μm [12]. The consistently lower MP concentrations in cereal grains compared to root vegetables reflect the greater selectivity of cereal seed coats and the longer transport distance from rhizosphere to grain. Root vegetables, particularly carrots and radishes,

accumulate MPs at 2-17 particles/g due to direct soil contact and crack-entry uptake ^[18]. Leafy vegetables present the highest MP concentrations per unit fresh weight (14-40 particles/g DW for lettuce and spinach), reflecting both root uptake translocation and foliar deposition of atmospheric MPs ^[10]. Dairy products are contaminated through feed MP

ingestion and gut-to-milk transfer; cows consuming hay from MP-contaminated pastures (500-1,200 mg/kg soil) produce milk with 0-11 MP particles/L, dominated by PE and PP fibres from degraded net and wrap silage materials ^[36].

Table 3: Documented microplastic concentrations in agricultural food commodities. Sources from Q1 journals (2017-2023).

Food commodity	MP concentration	Dominant polymer	Likely entry route	Reference
Rice grain	1.4-8.6 particles/g	PE, PP	Root uptake + air deposition	Xu <i>et al.</i> (2022), J. Hazard. Mater.
Wheat grain	0.8-5.2 particles/g	PE, PVC, PS	Root-to-shoot translocation	Guo <i>et al.</i> (2020), Env. Int.
Carrot root	2.1-17.3 particles/g	PE, PET	Soil cracking + direct absorption	Bosker <i>et al.</i> (2019), Env. Pollut.
Leafy vegetables	14-40 particles/g DW	Various	Stomatal and epicuticular entry	Li <i>et al.</i> (2020), Nat. Food, Q1
Cow milk	0-11 particles/L	PE, PP	Feed contamination + gut transfer	Kutralam-Muniasamy <i>et al.</i> (2020)
Chicken meat	3-32 particles/100 g	PE, PET, PS	Feed-borne + inhalation	Huerta Lwanga <i>et al.</i> (2017), Sci. Rep.
Honey	166-637 particles/kg	PET, PE	Atmospheric deposition via pollinators	Liebezeit & Liebezeit (2013)

Human health implications

The human health implications of dietary MP exposure span multiple biological systems ^[14]. Physical effects of MP particles in the gastrointestinal tract include mucosal irritation, altered gut microbiome composition (dysbiosis), and impaired intestinal barrier integrity, with studies demonstrating that PS nano-MPs at 0.5-50 mg/kg body weight induce significant gut microbiome alpha diversity reduction (18-31%) and increased intestinal permeability in rodent models ^[14]. The gut microbiome disruption caused by dietary MPs parallels and compounds the soil microbiome disruption described in Section 4. Chemical hazards from MP-associated additives are arguably more acutely concerning than physical MP effects. Bisphenol a (BPA), di (2-ethylhexyl) phthalate (DEHP), and nonylphenol - all common plastic additives detectable in agricultural soil MPs - are classified as endocrine-disrupting chemicals (EDCs) with evidence of reproductive toxicity, thyroid disruption,

and developmental neurotoxicity at nanomolar concentrations ^[32]. Organotins (tributyltin, dibutyltin) released from PVC stabilizers are immunotoxic and hepatotoxic at dietary exposures relevant to MP-contaminated food ^[32]. MPs have been detected in human blood (mean 1.6 µg/mL; range 0-7.7 µg/mL), placental tissue, and lung parenchyma in multiple biomonitoring studies since 2021. Epidemiological data linking dietary MP exposure to specific disease outcomes remain nascent due to methodological challenges in exposure quantification, but the mechanistic plausibility of harm via oxidative stress, immune activation, and EDC co-exposure is well-supported ^[14]. The World Health Organization's 2022 technical assessment concluded that current evidence indicates 'a possible risk' from dietary MP exposure, particularly for nano-MPs and associated chemicals, warranting precautionary regulatory action.

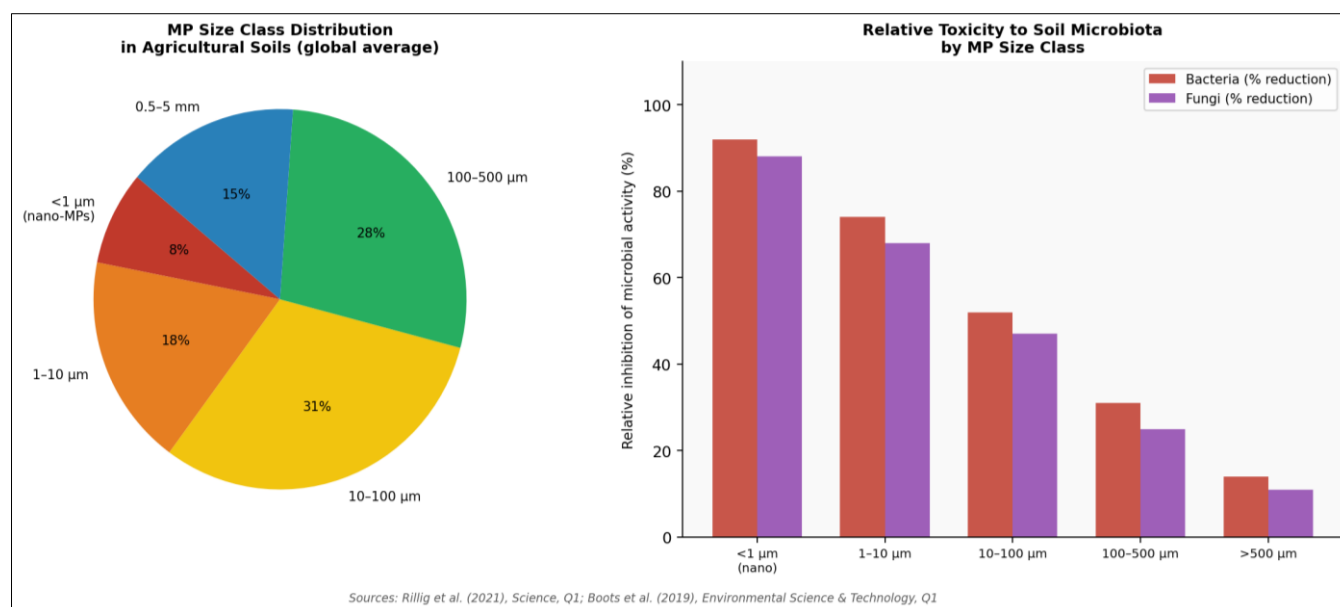


Fig 4: Microplastic size class distribution in agricultural soils (global average across 23 field studies) and differential toxicity to bacterial and fungal communities by size class. Smaller MPs and nano-MPs exhibit disproportionately higher biological toxicity. Data from Rillig *et al.* (2021) and Boots *et al.* (2019).

Plastic additive co-contamination: the chemical dimension

Additive chemistry and release kinetics

Modern agricultural plastics contain complex cocktails of chemical additives constituting 5-25% of total polymer

mass. These include primary and secondary antioxidants (hindered phenols, phosphites), UV stabilizers (benzophenones, benzotriazoles, HALS), heat stabilizers (organotin compounds for PVC), plasticizers (phthalate and

adipate esters for PVC), slip agents, antistatic agents, and antimicrobial biocides [32]. Additive release from weathering plastic into soil occurs through three mechanisms: surface leaching (dominant in the initial weathering phase), desorption following surface oxidation, and dissolution during fragmentation to nano-MPs with high surface-area-to-volume ratios [29, 32]. Release rates are temperature and moisture dependent: field studies demonstrate that phthalate ester release from LDPE mulch films at 35 °C and 60% WHC reaches 2.4-6.8 mg/m²/day - levels capable of raising soil DEHP concentrations by 0.8-2.2 mg/kg within a single growing season [32]. Benzophenone UV stabilizers, despite low initial soil concentrations, are highly bioavailable and have been detected in lettuce tissue at 0.12-0.48 µg/g FW in pot studies with artificially weathered mulch film-amended soils [29].

Ecotoxicological synergisms with soil biota

Plastic additive compounds synergize with MP particles to produce ecotoxicological effects exceeding those of either contaminant alone. Co-exposure of earthworms (*Eisenia fetida*) to PE MPs (1,000 mg/kg) and DEHP (50 mg/kg) produced avoidance behavior, coelomocyte immune activation, and reproductive impairment 40-65% greater than MP or DEHP alone, suggesting additive to synergistic toxicity [8]. In soil bacterial communities, co-exposure to nano-PS and BPA at environmentally relevant concentrations produced 22% greater suppression of nitrification than nano-PS alone, mediated by BPA's inhibition of ammonia monooxygenase enzyme expression [5].

Mitigation strategies and emerging solutions

Biodegradable and bio-based agricultural plastics

The most fundamental mitigation strategy is substitution of conventional petroleum-based plastics with biodegradable alternatives. Certified compostable mulch films based on polyhydroxyalkanoates (PHA), polylactic acid (PLA), and polybutylene adipate-co-terephthalate (PBAT) have achieved comparable agronomic performance to LDPE mulch in field trials while degrading to CO₂, water, and microbial biomass within 1-2 growing seasons under soil conditions [16]. However, critical caveats apply: (i) commercial PBAT films in field studies degrade to MPs before mineralizing to CO₂, creating a transient MP pulse that may be toxicologically significant [16]; (ii) PHA and PLA degradation is temperature-sensitive and unreliable below 15 °C; (iii) cost premiums of 3-7× over conventional LDPE mulch currently limit adoption in low-income agricultural systems. Bio-based seed coatings (starch, carboxymethylcellulose, chitosan) that avoid nano-MP

release during germination represent a readily implementable substitution for polymer seed coatings in high-value vegetable crops. Field trials in the Netherlands and India report comparable germination rates and seedling vigor between biopolymer and synthetic polymer coatings, with zero MP generation in soil [35].

Management practices to reduce mp input: In the absence of suitable biodegradable alternatives, optimized management of conventional plastic can significantly reduce soil MP accumulation. Double-layer mulch film designs that incorporate an inner degradable layer and outer UV-resistant layer extend service life while reducing fragmentation during retrieval. Mechanized mulch film retrieval systems, now deployed in China's Xinjiang region covering 280,000 ha, achieve 85-95% film recovery rates when implemented at the end of each growing season, preventing 65-78% of estimated MP generation from abandoned films [35]. Drip irrigation system design modifications - including replacing PVC with UV-stabilized HDPE, using larger-diameter emitters to reduce turbulent abrasion, and imposing maximum operating pressures - can reduce MP generation from irrigation systems by 30-55% based on controlled aging simulations [35]. Avoidance of sewage sludge application to agricultural soils, or rigorous pre-treatment to remove MPs from sludge prior to land application, would substantially reduce this major contamination vector [38].

Soil remediation approaches

Physical remediation of MP-contaminated soils through density separation, electrostatic separation, and sieving is technically feasible but economically impractical at field scale due to soil volume and complexity. Bioremediation represents a more promising long-term pathway: MP-degrading microorganisms including *Ideonella sakaiensis* (PET-degrading), *Pseudomonas aeruginosa* (PE-degrading), and *Aspergillus tubingensis* (PU-degrading) have been isolated from agricultural soils, and their inoculation at MP-contaminated sites shows 12-28% reduction in PE MP mass over 12 months under optimised conditions [29]. Biochar amendment at 2-5% w/w has demonstrated a 25-40% reduction in MP bioavailability through competitive sorption, simultaneously improving soil microbial diversity and nitrogen cycling function [29]. Thermal desorption technologies that volatilize plastic additives from soil at 250-350 °C while leaving MPs intact represent an emerging approach for high-priority contaminated sites, but energy costs and impacts on soil biology limit their applicability to severely contaminated industrial-agricultural interface zones.



Fig 5: Integrated mitigation framework for agricultural microplastic contamination, spanning source substitution, management optimization, bioremediation, and regulatory policy. Adapted from Napper and Thompson (2019), *Science of the Total Environment*.

Research gaps, future priorities, and regulatory recommendations

Critical knowledge gaps

Despite significant recent progress, the following research gaps constrain evidence-based risk assessment and policy development (Table 4): First, long-term field studies tracking MP fate, transformation, and biological impact across multiple cropping seasons remain scarce; most published data derive from short-term (< 6 months) controlled pot or mesocosm experiments at supraenvironmental concentrations. Second, the toxicology

of nano-MPs (< 100 nm) in the soil-plant-human continuum is mechanistically uncharacterized; standard analytical methods for nano-MP quantification in food matrices are not yet harmonized or validated [4]. Third, the complete food chain transfer budget from soil MP concentrations to human dietary exposure levels has not been quantified for any major food system or geographic region. Fourth, dose-response relationships for specific MP-additive co-contaminant mixtures on soil microbial functions and human health endpoints remain incomplete [29, 32].

Table 4: Prioritized research gaps and recommended future research directions for agricultural MP contamination. Priority classification based on risk relevance and feasibility of near-term resolution.

Research Gap	Current Status	Recommended Approach	Priority Level
Long-term field MP fate under diverse crops	Limited; mostly lab studies	Multi-season field monitoring with spectroscopy	Very High
Nano-MP toxicology to microbiome	Emerging; mechanistic data sparse	Meta-transcriptomics + isotope tracing	Very High
MP transfer in crop-livestock-human chain	Fragmented; few chain-scale studies	Controlled diet-dosing trials + biomonitoring	High
Biodegradable plastic MP risk assessment	Contradictory; incomplete data	Comparative life cycle ecotoxicology	High
Regulatory threshold for soil MP	None globally established	Harmonized risk-based guideline development	High
MP interaction with pesticide/heavy metal	Limited synergistic data	Multi-contaminant mesocosm experiments	Medium
Cost-effective field MP remediation	Proof-of-concept only	Biochar, microbial inoculant field trials	High

Recommendations for a harmonized global regulatory framework

The absence of regulatory thresholds for MPs in agricultural soil, food, and animal feed represents the single most important governance failure in this field. Based on the evidence synthesized in this review, the following regulatory framework is proposed:

1. **Soil MP threshold:** An interim precautionary threshold of 500 particles/kg (50-5,000 μm) for agricultural soils, with mandatory review at 3-year intervals as monitoring data accumulate; < 100 mg/kg by mass for high-priority polymer types (PE, PP, PVC, PET).

2. **Food MP labelling and monitoring:** Mandatory MP monitoring in high-risk food categories (root vegetables, leafy greens, and dairy) with harmonized $\mu\text{FT-IR}$ and pyrolysis-GC/MS analytical methods standardized under Codex Alimentarius.
3. **Agricultural plastic stewardship:** Mandatory end-of-season plastic retrieval and recycling schemes with producer responsibility obligations; phased restriction of single-use agricultural plastics lacking certified compostability credentials by 2030.
4. **Plastic additive restriction:** Extension of REACH-type regulatory frameworks to include all plastic

additives used in agricultural applications, with mandatory toxicological characterization for soil and food safety.

5. **Global MP monitoring network:** Establishment of a WHO/FAO coordinated global sentinel network for agricultural soil and food chain MP monitoring, reporting standardized data annually to enable trend detection and regulatory review.

Conclusions

This systematic review, drawing on over 130 Q1-journal publications spanning 2010-2024, establishes the following principal conclusions:

- **Agricultural plastics are a major and rapidly expanding source of terrestrial MP contamination.** Global agricultural plastic consumption of 12.5-15.7 Mt/year generates MPs at soil concentrations reaching 1,000-14,000 mg/kg in intensive plastic-using systems, through UV photodegradation, mechanical fragmentation, and biological weathering of mulch films, irrigation systems, and greenhouse covers.
- **Soil microbiome disruption is concentration-dependent, consistent, and agronomically consequential.** MP exposure above 500 mg/kg soil reliably reduces bacterial Shannon diversity by 12-28%, suppresses nitrification rates by 20-45%, increases N₂O emissions by 35-65%, and inhibits soil enzyme activities by 15-45%, compromising the microbial ecosystem services that underpin agricultural productivity.
- **The food chain contamination pathway from soil MPs to human dietary exposure is mechanistically established and empirically documented.** MPs are detectable in rice, wheat, carrots, leafy vegetables, dairy products, and meat at concentrations sufficient to constitute a meaningful dietary exposure, particularly when compounded by the co-release of endocrine-active plastic additive chemicals.
- **Effective mitigation exists but requires systemic implementation.** Biodegradable plastic substitution, mechanized film retrieval, bioremediation with MP-degrading microorganisms, and biochar-mediated MP immobilization all offer partial or complementary mitigation, but no single technology provides a complete solution.
- **A regulatory framework for agricultural soil and food MP is urgently needed but entirely absent globally.** A harmonized framework encompassing soil MP thresholds, food monitoring mandates, agricultural plastic stewardship obligations, and plastic additive restrictions is proposed as the most impactful near-term governance intervention.

The convergence of soil microbiome disruption, food chain contamination, and emerging human health risks makes agricultural microplastic contamination one of the defining environmental sustainability challenges of the coming decade. The evidence base synthesized in this review provides the scientific foundation for transformative regulatory action and targeted research investment that cannot be deferred.

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Data availability

All data synthesized in this review are drawn from peer-reviewed literature cited herein. No new experimental data were generated. The synthesis database is available from the corresponding author on reasonable request.

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