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Microplastics and nanoplastics in soil–plant systems: mechanistic evidence, agronomic relevance, and limits of inference

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A B S T R A C T

Microplastics and nanoplastics (MPs/NPs) are increasingly reported in agricultural soils, yet their significance for crop production, soil function, contaminant transfer, and food safety remains difficult to evaluate. The central challenge is not merely documenting particle occurrence, but determining when mechanistic observations support defensible agronomic inference. Here, we combine bibliometric mapping of Scopus-indexed literature published between 2015 and 2025 (n = 1815), a structured critical synthesis of representative empirical evidence, and a claim-specific interpretive framework for MP/NP research in soil–plant systems. Bibliometric analysis characterizes the field's structure and thematic development, whereas empirical synthesis examines how evidence supports biological, functional, transfer, and agronomic claims. Bibliometric patterns indicate rapid expansion of the literature, but limited integration of crop-cycle performance, edible-compartment measurements, multitemporal field evidence, and integrated soil–microbiome–plant endpoints. Across the representative evidence synthesized here, responses to MPs/NPs are strongly context dependent and are modulated by polymer identity, particle size, morphology, aging status, soil matrix, exposure metric, exposure duration, crop species, and co-contaminants. Physiological markers, microbial taxonomic shifts, sorption assays, tissue-associated particle signals, and short-term responses are mechanistically informative, but they do not by themselves establish field-level soil degradation, productivity loss, contaminant-vector effects, edible-tissue relevance, or food-safety implications. The proposed framework separates particle occurrence, validated exposure, mechanistic response, microbial functional response, crop performance, contaminant transfer, edible-compartment relevance, and agronomic inference according to the evidence required for each claim. Under this framework, the representative evidence primarily supports mechanistic plausibility and bounded soil–plant interpretation, whereas generalized field-level agronomic claims require stronger analytical validation, exposure realism, endpoint alignment, temporal structure, material realism, and claim-specific evidence. Rather than classifying MPs/NPs as uniformly harmful or harmless, this review defines how evidence should be configured, interpreted, and limited to support transparent, defensible inference in agricultural systems.

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List of abbreviations:

ARGs	Antibiotic resistance genes
ASVs	Amplicon sequence variants
LOD	Limit of detection
LOQ	Limit of quantification
MDA	Malondialdehyde
MPs	Microplastics
NPs	Nanoplastics
OTUs	Operational taxonomic units
PCoA	Principal coordinates analysis
ROS	Reactive oxygen species
SOC	Soil organic carbon
SPAD	Soil Plant Analysis Development chlorophyll index

1. Introduction

Global plastics production increased to 413.8 Mt in 2023, reflecting the continued expansion of polymer use worldwide, while the plastics lifecycle remains poorly circular, with only about 9% of plastic waste ultimately recycled globally and substantial fractions still incinerated, landfilled, mismanaged, or leaked into the environment [1–3]. These imbalances favor continued plastic leakage into agroecosystems, where agricultural soils receive plastic inputs through mulch films, irrigation materials, greenhouse covers, composts, biosolids, fertilizers, and other amendments [4,5]. Estimated plastic inventories in agricultural soils exceed marine inventories by several-fold, and concentrations up to 7400 particles kg^{-1} have been reported in intensive agricultural systems [6,7]. These data establish agricultural soils as important exposure compartments, but exposure evidence alone does not determine agronomic relevance. The central issue is no longer only whether plastic particles occur in agricultural soils, but whether the evidence generated in soil–plant studies is strong enough to support claims about soil function, crop performance, contaminant transfer, edible-tissue relevance, or field-level agronomic inference.

Unlike molecular contaminants, microplastics (MPs) and nanoplastics (NPs) are solid particles whose behavior depends on polymer identity, particle size, morphology, surface chemistry, aging status, and interactions with the surrounding matrix [8,9]. We define MPs as particles between 1 μm and 5 mm, and we operationally define NPs as particles below 1 μm; a threshold we retain, while recognizing narrower <100 nm frameworks, to capture the submicrometric fragmentation spectrum relevant to soil–plant exposure and uptake studies [10,11]. Weathering, oxidation, abrasion, biological colonization, and secondary fragmentation modify surface area, roughness, charge, functional groups, and sorption behavior [12–14]. These transformations affect interactions with soil minerals, organic matter, roots, rhizosphere microorganisms, and co-occurring contaminants. The same polymer may therefore support different interpretations depending on whether it is studied as a pristine particle, weathered fragment, mulch-derived residue, biofilm-associated surface, or mixed material assemblage [15–17].

Analytical uncertainty remains a primary constraint. Soil organic matter, mineral particles, plant residues, pigments, and airborne fibers interfere with particle extraction, classification, and polymer confirmation. Matrix-specific workflows, contamination controls, procedural blanks, recovery assessment, and spectroscopic or thermal confirmation are not technical details external to agronomic interpretation; they determine whether the particle signal used for downstream biological or field inference is reliable [18]. Diffuse agricultural inputs further complicate interpretation because organic amendments introduce plastic particles through different pathways, particle conditions, and chemical backgrounds [19–21]. Without validated analytical workflows and source-aware exposure characterization, we cannot confidently link a biological response to a defined MP/NP exposure scenario.

Current evidence supports the mechanistic plausibility that MPs/NPs can affect multiple layers of soil–plant systems, including soil physical-hydraulic properties, nutrient dynamics, microbial communities, plant physiological responses, contaminant behavior, and tissue-level particle associations. Controlled studies often detect pronounced responses under simplified matrices, high exposure levels, short durations, homogeneous particles, or hydroponic and pot-based conditions. Field-based and soil-based studies reveal more heterogeneous responses where exposure history, soil texture, organic matter, hydrology, crop management, weathering, and biological feedbacks operate simultaneously [22,23]. This difference does not invalidate controlled studies; it defines their inferential scope. Hydroponic systems can clarify uptake mechanisms, oxidative-stress markers can characterize physiological sensitivity, microbial profiles can document community restructuring, and sorption assays can describe contaminant interaction. However, we cannot automatically convert these endpoints into claims about field-scale soil degradation, crop productivity loss, vector effects, food-safety relevance, or long-term agronomic impact.

In this review, the translational gap refers to the mismatch between mechanistic observations generated under specific analytical, exposure, material, and endpoint conditions and the level of evidence required to support agronomic claims. This gap arises when we escalate evidence from one inferential level to another without the required analytical validation, exposure realism, endpoint alignment, temporal support, or material attribution. Particle occurrence does not equal validated exposure; hydroponic or high-dose pot responses do not equal soil-based agronomic inference; physiological markers do not equal productivity outcomes; microbial taxonomy does not equal realized soil function; sorption does not equal vector effect; tissue detection does not equal food-safety relevance; and pristine single polymers do not represent aged agricultural residues by default. These limitations are further shaped by the regional concentration of the literature, the prevalence of short-term controlled experiments, the scarcity of multi-season or legacy-paired designs, and the limited use of designs able to disentangle mixed polymers, additives, aged particles, and co-contaminants.

This review focuses strictly on the terrestrial soil–microbiome–plant continuum and does not address aquatic plastic pollution, human dietary risk modeling, or life-cycle assessment of agricultural plastics, except where these topics directly inform soil–plant inference. To address the translational gap, we integrate a bibliometric analysis of scientific production with an empirical synthesis of representative evidence across physical, biogeochemical, microbial, plant-response, transfer, and agronomic domains. Building on this integration, we develop a claim-specific inference framework that links analytical validity, exposure realism, endpoint alignment, temporal structure, material realism, and claim scope. Our objective is not to classify MPs/NPs as uniformly harmful or harmless, but to define the evidentiary conditions under which occurrence, mechanistic response, transfer, productivity, edible-tissue relevance, and agronomic inference become defensible. In doing so, we provide a structured basis for designing and interpreting MP/NP soil–plant studies according to the claims they seek to support.

2. Materials and methods

2.1. Study design

This study was designed as a critical review integrating bibliometric mapping, structured narrative mechanistic synthesis, and an agronomic inference framework. The bibliometric analysis characterizes the research landscape and identifies thematic patterns in the literature on microplastics and nanoplastics in agricultural soil–plant systems. The mechanistic synthesis organizes representative empirical evidence across the soil–microbiome–plant continuum. The agronomic inference framework evaluates how different types of evidence support, limit, or fail to support claims related to soil function, microbial responses, plant performance, contaminant transfer, edible-compartment relevance, and agronomic inference.

The study was not designed as a systematic review or meta-analysis.

No pooled effect-size estimation was performed because the selected studies differed substantially in polymer type, particle size, morphology, exposure metric, soil or growth matrix, exposure duration, plant species, and measured endpoints. Accordingly, the empirical synthesis should be interpreted as a structured critical synthesis of representative evidence rather than as an exhaustive assessment of all available studies.

No PRISMA flow diagram, formal risk-of-bias assessment, certainty-of-evidence grading, or pooled quantitative synthesis was applied. Therefore, this review does not estimate pooled effects or assign formal evidence certainty; instead, it evaluates the inferential conditions under which specific claims about MP/NP effects in soil–plant systems become bounded, plausible, or unsupported.

2.2. Bibliometric analysis

2.2.1. Data source and search strategy

Bibliometric records were retrieved from Scopus (Elsevier) using an advanced search executed on February 8, 2026, at 23:55 (UTC-5). The publication window was restricted to 2015-2025 using PUBYEAR >2014 AND PUBYEAR <2026. The search was applied to TITLE-ABS-KEY fields and was structured into two components. The first component retrieved records addressing microplastics or nanoplastics in agricultural, farmland, cropland, field soil, edaphic, or rhizosphere contexts. The second component expanded retrieval by including polymer-specific terms relevant to agroecosystems while retaining explicit reference to microplastics or nanoplastics and agricultural soil contexts. Broader particle descriptors such as "plastic particle", "plastic fragment", and "plastic fiber" were included to improve retrieval sensitivity because some soil–plant studies describe MP/NP exposure using morphology-based terminology rather than explicit microplastic or nanoplastic labels.

The Boolean query was:

((TITLE-ABS-KEY (microplastic* OR "micro-plastic*" OR nano-plastic* OR "nano plastic*" OR "plastic particle*" OR "plastic fragment*" OR "plastic fiber*" OR "plastic fibres" OR "plastic microfiber*" OR "plastic microfibre*" OR microbead* OR "plastic microbead*") AND TITLE-ABS-KEY ("agricultural soil*" OR "farmland soil*" OR "farm soil*" OR cropland* OR farmland* OR "arable soil*" OR "cultivated soil*" OR "agricultural land*" OR agroecosystem* OR "field soil*" OR rhizosphere*)) OR (TITLE-ABS-KEY ((polyethylene OR polypropylene OR polystyrene OR "polyvinyl chloride" OR "polyethylene terephthalate" OR "polylactic acid" OR "polyhydroxyalkanoate*" OR "polybutylene succinate" OR "polybutylene adipate terephthalate") AND (microplastic* OR "micro-plastic*" OR nanoplastic* OR "nano plastic*" OR "plastic particle*" OR "plastic fragment*" OR "plastic fiber*" OR "plastic fibres")) AND TITLE-ABS-KEY ("agricultural soil*" OR "farmland soil*" OR "farm soil*" OR cropland* OR farmland* OR "arable soil*" OR "cultivated soil*" OR agroecosystem* OR "field soil*" OR rhizosphere*))) AND PUBYEAR >2014 AND PUBYEAR <2026.

Records retrieved by overlapping Boolean components were exported as unique Scopus records; no additional deduplication was performed beyond the automatic export process. No formal language restriction was applied; however, the search string was constructed in English, which may favor records using English-indexed terminology. Accordingly, the corpus should be interpreted as English-query, Scopus-indexed literature rather than as the complete global evidence base. No restrictions were applied regarding document type, subject area, or source type. Records were exported in CSV format, including title, abstract, Author Keywords, authors, affiliations, source title, publication year, cited references, DOI, and citation counts. The final corpus consisted of 1815 records.

2.2.2. Bibliometric indicators and collaboration metrics

Bibliometric indicators were calculated from the Scopus metadata. These included annual publication output, document type distribution, source structure, subject-area classification, citation counts by publication year, country-level production, and author-, institutional-, and country-level collaboration patterns.

For temporal analyses, Documents(y) was defined as the number of documents published in year y, and Citations(y) was defined as the total number of Scopus-indexed citations recorded for documents published in year y at the time of data retrieval. Citation counts were interpreted descriptively because older publication cohorts had longer citation windows than recent cohorts.

Subject-area distribution was based on Scopus classifications. Because individual documents may be assigned to more than one subject area, subject-area proportions were treated as multi-label classifications rather than mutually exclusive categories.

Country-level production was calculated using full counting based on author affiliation countries. Full counting assigns one contribution to each affiliated country per document, meaning that a document with authors from three countries contributes one count to each country. This approach was retained because the aim was to describe absolute production volume rather than normalized collaborative intensity. International collaboration was represented through a country–country co-authorship matrix, where link weights corresponded to the number of co-authored documents between country pairs.

Institutional collaboration was derived from affiliation metadata. When required, institutional names were inspected and harmonized to reduce fragmentation caused by spelling variants, abbreviations, or alternative institutional designations. Institutional links represented co-authorship relationships among institutions within the same document.

2.2.3. Keyword normalization and network analysis

Semantic analysis was based on Author Keywords. Before frequency analysis and network construction, lexical normalization was performed in R using a predefined replacement dictionary to harmonize singular/plural forms, spelling variants, hyphenation, British/American spelling, polymer names, and chemical variants.

Network analyses used VOSviewer v1.6.20. Co-authorship analysis was conducted at the author level (minimum 15 documents per author). Keyword co-occurrence used Author Keywords (minimum 20 occurrences per term). Full counting and association-strength normalization were applied. Default clustering parameters (resolution = 1.00; minimum cluster size = 1) were retained.

Country–country collaboration maps, chord diagrams, temporal keyword heatmaps, and supplementary visualizations were generated in R. Input files, processed datasets, replacement dictionaries, bibliometric matrices, VOSviewer map files, R scripts, and configuration files were retained for internal verification of the bibliometric workflow.

2.3. Structured narrative mechanistic synthesis

2.3.1. Scope and boundaries of the synthesis

The mechanistic synthesis was conducted as a structured narrative review supported by representative studies from the bibliometric corpus and, when necessary, by additional full-text sources identified through reference checking. Additional sources were included only when they met the eligibility criteria defined in Section 2.3.2 and contributed evidence to at least one predefined inferential domain.

The synthesis organizes empirical and field-context evidence across the soil–microbiome–plant continuum and identifies recurrent methodological constraints affecting agronomic interpretation. Tables 1 and 2 summarize the representative evidence base, including 23 unique empirical or field-context sources selected to represent major functional and inferential domains: soil physical–hydraulic responses, biogeochemical processes, contaminant mobility, rhizosphere and microbial responses, plant physiological responses, crop-performance endpoints, and tissue-level particle evidence. Table 3 was developed separately as a claim-specific inference matrix and is not part of the empirical evidence count.

The synthesis focuses on studies reporting MP/NP effects on soil

Table 1
Edaphic and microbial evidence linking agricultural MP/NP exposure to mechanistic responses and translational bottlenecks.

Polymer/particle type	Exposure context	Exposure realism	Main edaphic response	Microbial/functional response	Evidence level/ bottleneck	Agronomic interpretation/inference limit	References
PVC fragments	Controlled pot exposure; tropical silt loam; elevated dose range	Moderate–low	Altered porosity, C leaching, and N-related soil properties	Reduced enzymatic activity and microbial diversity indicators	Mechanistic plausibility/dose-realism and pot-to-field gaps	Supports mechanistic evidence for structural and microbial alteration under controlled exposure. Does not establish generalized field-level soil degradation or crop productivity loss.	[24,25]
PE/LDPE films or residues	Long-term mulch legacy; loamy sand; field/pot systems	High, but confounded	Altered aggregation and hydraulic behavior	Reduced fungal diversity and redox-related microbial responses	Agronomic relevance/ legacy-exposure confounding	Supports the relevance of chronic mulch residues for soil structure and microbial response. Does not isolate MP-specific effects from macroplastic residues or long-term management history.	[26,27]
PS nanoplastics	Hydroponic NP exposure; 50–100 nm; soil-free system	Low	Altered micronutrient availability under solution-based exposure	Enrichment of selected rhizosphere taxa and ARG-associated signals reported under controlled conditions; functional transfer was not demonstrated	Mechanistic plausibility/ hydroponic-to-soil and analytical-validity gaps	Supports NP interaction mechanisms under soil-free exposure. Does not support soil-based agronomic inference without validation in real edaphic matrices. ARG-associated signals should not be interpreted as HGT.	[23]
PP fibers/mask-derived particles	Microcosm exposure; peri-urban cropland; silt loam	Moderate–low	Changes in soil-quality indicators, Nmin, SOM, and electrical conductivity	Altered enzyme activity and microbial richness/evenness	Biological response/ dose-realism and microcosm-to-field gaps	Supports polymer-specific restructuring of soil biological indicators. Does not demonstrate improved or degraded soil health at field scale without crop-performance validation.	[28]
PLA/PBAT biodegradable particles	Biodegradable mulch residue; purple soil; controlled or field-aligned systems	Moderate	Changes in DOC, SOC, and pH	Altered microbial diversity, fungal community structure, and metabolic activity	Biological response/ biodegradable-polymer assumption gap	Supports the interpretation that biodegradable residues can affect soil C dynamics and microbial function. Does not support assuming agronomic neutrality without field validation.	[15,29, 30]
PA nylon fibers	Pot exposure; Andisol; acidic volcanic soil context	Moderate–low	Altered N availability and N-cycle-related soil processes	Altered N-related microbial niches and enzyme-activity vector parameters reported under controlled conditions	Mechanistic plausibility/dose-realism and pot-to-field gaps	Supports N-cycle perturbation under controlled edaphic conditions. Does not establish field-level N-use efficiency effects or crop productivity outcomes.	[22,31]
PET/PES particles or fibers	Controlled soil exposure; floodplain or silt loam context	Moderate	Increased heavy-metal mobility or bioavailability reported	Altered microbial community or network structure	Agronomic relevance/ contaminant-interaction-to-vector-effect gap	Supports contaminant-interaction mechanisms. Does not justify a complete vector-effect claim unless polymer presence, contaminant mobility, and biological uptake occur in the same system.	[6,32]
ABS/EVA resins	Controlled exposure; soil with xenobiotic or antibiotic co-contaminants	Low–moderate	Altered xenobiotic sorption or bioavailability	Microbial metabolic or biomarker shifts reported	Mechanistic plausibility/single-polymer-to-field-mixture gap	Supports altered contaminant behavior under controlled exposure. Does not establish field-scale contaminant transfer or food-safety relevance.	[33,34]
Mixed polymers/ field assemblages	Agricultural fields receiving mixed plastic inputs from mulch residues, biosolids, sludge, compost, organic fertilizers, or wastewater irrigation	High, but heterogeneous and confounded	Context-dependent exposure and soil accumulation patterns; edaphic responses remain less systematically characterized than in single-polymer studies	Functional effects of mixed and aged polymer assemblages remain less resolved than single-polymer responses	Field-context or review-level evidence/ single-polymer-to-field-mixture gap	Supports the need for aged and mixed-polymer studies under realistic agricultural conditions. Does not support direct extrapolation from single-polymer experiments to field mixture scenarios.	[35–40]

Notes: Evidence levels distinguish mechanistic plausibility, biological response, microbial functional response, agronomic relevance, field-context evidence, and field-level inference. Translational bottlenecks identify the main limitation preventing direct extrapolation from edaphic or microbial responses to agronomic inference. Quantitative endpoint values, dose details, extraction fields, and verification status are provided in Supplementary Table S1. Microbial taxonomic shifts were not interpreted as functional disruption unless functional endpoints were reported. Contaminant sorption or mobility was not interpreted as a complete vector effect unless polymer presence, contaminant mobility, and biological uptake or transfer were reported within the same experimental system.
Abbreviations: ARGs, antibiotic resistance genes; DOC, dissolved organic carbon; MPs, microplastics; Nmin, mineralizable nitrogen; NPs, nanoplastics; SOC, soil organic carbon; SOM, soil organic matter.

Table 2
Plant-level evidence linking MP/NP exposure to physiological responses, crop-performance endpoints, contaminant interactions, and translational bottlenecks.

Crop/plant system	Polymer/ particle type	Exposure context	Exposure realism	Plant-response domain	Contaminant/ tissue-level evidence	Endpoint strength/ bottleneck	Agronomic or food-safety interpretation/ inference limit	References
Peanut/ legume system	PVC fragments	Controlled pot exposure; tropical silt loam; elevated dose range	Moderate–low	Growth impairment, root alteration, oxidative-stress response, and N-transporter suppression reported	Cd/Pb association and root-level tissue signals reported under controlled conditions; edible-tissue evidence not established	Moderate/pot-to-field, physiology-to-yield, and root-association-to-internalization gaps	Supports plant stress and growth-response mechanisms under controlled exposure. Does not establish field-level yield loss, confirmed edible-tissue accumulation, or food-safety relevance.	[22,24]
Wheat/cereal system	PE/LDPE films or residues	Long-term mulch legacy; loamy sand; field/pot systems	High, but confounded	Reduced emergence or early establishment, altered leaf development, and sugar/starch metabolism reported	Paraquat, chlorpyrifos, and PAEs may co-occur in mulch-residue contexts; polymer-specific causal attribution remains limited	Moderate to high if field-based/ legacy-exposure and early-growth-to-crop-cycle gaps	Supports agronomic relevance for crop establishment under chronic mulch legacy. Does not isolate MPs-specific effects from macroplastic residues, co-contaminants, or long-term management history.	[26,27]
Soybean/ legume system	PS nanoplastics	Hydroponic NPs exposure; 50–100 nm; soil-free system	Low	Chlorophyll-related response, reduced N-fixation efficiency, and altered flavonoid/ phenylpropanoid pathways reported	Cd interaction and ARG-associated signals reported; HGT and field-level transfer were not demonstrated	Low to moderate/ hydroponic-to-field, marker-to-productivity, and contaminant-interaction gaps	Supports mechanistic evidence for NP effects on physiological and symbiotic pathways. Does not establish productivity loss in soil-grown legumes, HGT, or field-scale contaminant-transfer effects.	[23]
Tobacco/ soil–plant pot system	PP fibers/mask-derived particles	Pot or controlled soil exposure; peri-urban cropland or silt loam context	Moderate–low	Altered stomatal conductance, photosynthesis, and soil-mediated plant response reported	UV-fragmentation and pathogen-associated contexts reported; disease outcome was not demonstrated	Low to moderate/pot-to-field and marker-to-productivity gaps	Supports soil-mediated plant physiological response under controlled exposure. Does not demonstrate crop-performance loss, disease risk, or field-level agronomic impact.	[28,41, 42]
Maize/ vegetable crop system	PLA/PBAT biodegradable particles	Biodegradable mulch residue; purple soil; controlled or field-aligned systems	Moderate	Dose-dependent growth, chlorophyll-related response, aquaporin regulation, and lignification-related gene expression reported	Shift toward fungal taxa including *Fusarium/ Alternaria* reported; pathology endpoints were not demonstrated	Moderate/ biodegradable-polymer assumption, physiology-to-yield, and disease-association-to-pathology gaps	Supports dose-dependent plant response to biodegradable residues. Does not prove consistent yield benefit, yield loss, or disease outcome without crop-cycle and pathology validation.	[29,43, 44]
Lupine/ legume system	PA nylon fibers	Pot exposure; Andisol; acidic volcanic soil context	Moderate–low	Germination, oxidative-stress, nitrate-transporter, and nutrient-related responses reported	Ni-retention association reported; contaminant transfer and	Low/pot-to-field, marker-to-productivity, and contaminant-interaction gaps	Supports plant stress and nutrient-transport perturbation under controlled	[22,31]

(*continued on next page*)

Table 2 (*continued*)

Crop/plant system	Polymer/ particle type	Exposure context	Exposure realism	Plant-response domain	Contaminant/ tissue-level evidence	Endpoint strength/ bottleneck	Agronomic or food-safety interpretation/ inference limit	References
					edible-tissue relevance were not established		edaphic exposure. Does not establish field-level productivity effects, N-use efficiency outcomes, or food-safety relevance.	
Lettuce, radish, carrot, or related vegetable systems	PET/PES particles or fibers	Controlled soil exposure; floodplain, silt loam, or contaminated soil contexts	Moderate	Root growth, nutrient uptake, physiological stress, or crop-specific growth responses reported	Pb, Ni, Cu mobility or uptake reported in selected systems; edible-tissue exposure assessment remains system-specific	Moderate/ contaminant-interaction-to-food-safety and cross-crop extrapolation gaps	Supports crop-specific contaminant-interaction and plant-response mechanisms. Does not justify generalized food-safety claims or extrapolation across vegetable crops without tissue-specific exposure assessment.	[6,32]
Plant system under antibiotic or xenobiotic exposure	ABS/EVA resins	Controlled soil or growth-matrix exposure with SMX or xenobiotic co-contaminants	Low–moderate	Modulated phytotoxicity, antioxidant response, steroid-biosynthesis response, or CAT-related response reported	SMX or xenobiotic bioavailability changes reported under controlled exposure	Low to moderate/ contaminant-interaction-to-food-safety and single-polymer-to-field-mixture gaps	Supports altered xenobiotic bioavailability and plant-response mechanisms. Does not demonstrate field-scale contaminant transfer or food-safety risk.	[33,34]
Mixed polymer field assemblages	Mixed MPs/ NPs, aged particles, additives, and co-contaminants	Agricultural systems receiving mulch residues, biosolids, sludge, compost, organic fertilizers, wastewater irrigation, or mixed plastic inputs	High, but heterogeneous and confounded	Plant-level responses under realistic mixed exposure remain less resolved than single-polymer responses	Co-occurrence of polymers, additives, metals, antibiotics, pesticides, and pathogens may occur, but causal attribution is difficult	Field-context, not quantifiable/ single-polymer-to-field-mixture and contaminant-mixture gaps	Supports the need for field studies using aged and mixed polymer assemblages. Does not support direct extrapolation from pristine single-polymer experiments to real crop systems.	[35,37, 38]

Notes: Physiological and molecular markers, including SPAD, MDA, proline, chlorophyll, and gene-expression responses, were not interpreted as yield loss unless crop-performance endpoints, such as mature biomass, fruit number, fruit weight, grain yield, or harvestable tissue quality, were reported. Enzyme activity, including CAT, was interpreted as a biochemical response, not as direct evidence of crop productivity. Root-associated or tissue-level signals were not interpreted as confirmed internalization unless validated localization methods were reported. Food-safety relevance requires validated edible-tissue detection together with exposure-oriented interpretation. ARG-associated signals were not interpreted as horizontal gene transfer, and fungal-taxa shifts were not interpreted as disease outcomes without pathology endpoints. Quantitative values, dose details, and verification status should be provided in Supplementary Table S2.
Abbreviations: ARGs, antibiotic resistance genes; CAT, catalase; HGT, horizontal gene transfer; MDA, malondialdehyde; MPs, microplastics; NPs, nanoplastics; PAEs, phthalate esters; SMX, sulfamethoxazole; SPAD, soil plant analysis development chlorophyll index.

physical properties, hydraulic behavior, carbon and nitrogen cycling, nutrient availability, contaminant mobility, rhizosphere microbiome structure or function, plant physiological stress, nutrient uptake, biomass, yield-related endpoints, or tissue-level particle detection. Representative studies do not provide statistical representativeness of the full bibliometric corpus nor should they be read as an exhaustive census. Instead, they define the range of experimental configurations and inferential bottlenecks in MP/NP soil–plant research. Bibliometric records characterize the structure and thematic development of the field, whereas empirical and field-context sources support the mechanistic synthesis.

2.3.2. Selection of representative studies

Representative studies were selected using a stratified narrative approach covering predefined functional and inferential domains. The selection criteria were reported to improve transparency and to delimit the scope of interpretation, rather than to support exhaustive or statistically representative evidence synthesis.

Selection was guided by keyword co-occurrence clusters and by the need to cover polymer types, particle morphologies, exposure systems, soil or growth matrices, crop or plant species, exposure durations, analytical approaches, and endpoint classes relevant to agronomic inference.

Studies were included in Tables 1 and 2 when they met the following criteria: polymer type was instrumentally identified or explicitly characterized; quantitative soil, microbial, plant physiological, contaminant-transfer, tissue-level, biomass, yield-related, or agronomic endpoints were reported; exposure conditions were sufficiently described, including polymer type, particle morphology, dose or exposure metric, duration, and experimental system; the study involved an agricultural,

Table 3
Claim-specific evidence thresholds, translational bottlenecks, and defensible inference limits for MP/NP soil–plant research.

Inferential domain	Claim	Minimum evidence threshold	Insufficient evidence	Translational bottleneck	Defensible interpretation	Evidence required for escalation	Current inferential support	References
Soil function	Soil physical degradation	Validated polymer exposure; soil-based matrix; structural or hydraulic endpoints, including bulk density, porosity, aggregate stability, infiltration, water retention, or hydraulic conductivity.	Particle occurrence; visual contamination; short-term high-dose pot assays; physical responses reported without soil texture, dose, or management context.	Dose-realism; soil-texture dependence; pot-to-field extrapolation.	MPs/NPs exposure can modify soil physical–hydraulic behavior under specific polymer, dose, soil texture, and management conditions.	Multi-site or field-aligned studies linking polymer load with soil structure, hydraulic behavior, crop-cycle conditions, and management history.	Moderate–High	[45–47]
Soil function	Soil biogeochemical disruption	SOC fractions; microbial necromass; N mineralization; NH_4^+/NO_3^- dynamics; ammonia volatilization; nutrient lability; enzyme activity; DGT-based nutrient availability; validated soil-quality indices.	Isolated nutrient concentration; shoot biomass alone; taxonomic shifts alone; short-term chemical changes disconnected from process-level interpretation.	Endpoint-to-process gap; short-term-to-long-term gap; unit-comparability gap.	MPs/NPs exposure can alter carbon and nutrient-cycling pathways under defined soil, polymer, dose, and duration contexts.	Long-term soil-based studies linking biogeochemical shifts with soil function, nutrient supply, plant uptake, and crop performance.	Moderate–High	[22, 48–50]
Microbial function	Microbial functional disruption	Functional genes; enzyme activity; respiration; heat-flow dynamics; metabolic pathways; nutrient-cycling genes; microbial network stability.	Shannon diversity; Chao1 richness; ASVs; PCoA separation; community composition without functional validation.	Taxonomy-to-function gap.	MPs/NPs exposure can disrupt microbial function when taxonomic restructuring is accompanied by functional, metabolic, or network-level evidence.	Integrated rhizosphere studies linking microbial function with soil biogeochemistry, nutrient cycling, plant response, and field-relevant exposure.	High	[29,43,50, 51]
Plant response	Plant physiological stress	Validated exposure; marker-level endpoints, including SPAD, chlorophyll, MDA, ROS, antioxidant activity, proline, ion flux, transporter expression, photosynthetic traits, or stress-related metabolites.	Germination acceleration; isolated marker change; physiological response interpreted as crop productivity or field-level agronomic loss.	Marker-to-productivity gap.	MPs/NPs exposure can induce physiological, oxidative, photosynthetic, or metabolic stress responses under defined exposure conditions.	Crop-cycle studies linking stress markers with biomass partitioning, yield components, harvestable quality, or productivity decline.	Strong for stress; weak–moderate for productivity	[44,52]
Crop performance	Crop productivity loss	Mature biomass; fruit number; fruit weight; grain yield; tuber yield; harvestable biomass; marketable yield; full crop-cycle performance under soil-based exposure.	SPAD; chlorophyll; transpiration; MDA; root length; shoot length; germination; seedling biomass; short-term vegetative biomass.	Marker-to-productivity gap; crop-cycle-duration gap; pot-to-field gap.	MPs/NPs exposure can reduce crop performance in specific controlled soil systems when yield-related endpoints are directly measured.	Field-aligned or semi-field studies measuring harvestable yield across complete crop cycles and realistic exposure scenarios.	Moderate	[32,46,53]
posTransfer and exposure	Contaminant vector effect	Polymer characterization; contaminant sorption/desorption; altered geochemical fractionation; mobility; bioavailability; biological uptake or tissue transfer within the same exposure system.	Sorption alone; desorption alone; contaminant co-occurrence in soil; metal concentration without demonstrated MP-mediated transfer.	Sorption-to-transfer gap.	MPs can act as contaminant vectors when polymer presence modifies contaminant mobility and biological uptake or transfer in the same system.	Studies integrating polymer characterization, contaminant speciation, soil bioavailability, plant uptake, and tissue-level transfer.	Moderate–High when uptake is measured; low when restricted to sorption	[6,33,54, 55]
Transfer and exposure	Particle internalization	Validated tissue localization; mass balance; tracer confirmation; contamination control; distinction between external adhesion and internal particle presence.	Fluorescence signal alone; root-surface association; rhizosphere presence; tissue-associated particles without localization and contamination controls.	Root-association-to-internalization gap; localization-validity gap.	Soil-based or standardized biotest systems can support particle phytoavailability or root-level internalization when localization and mass-balance criteria are met.	Tissue-specific imaging or tracer-based studies confirming internalization, translocation, and compartmental distribution across crop organs.	Moderate–High	[56,57]
Food-chain transfer	Edible-tissue accumulation	Validated polymer or particle detection in edible compartments; contamination control; tissue-specific localization; harvestable-organ sampling.	Root internalization; root adhesion; detection in non-edible tissues; physiological stress without edible-organ evidence.	Internalization-to-edible-tissue gap.	MP/NP-associated particles or contaminants can accumulate in edible structures in selected controlled systems when tissue-level detection is validated.	Field-relevant edible-crop studies combining validated detection, exposure realism, contamination control, and harvestable tissue analysis.	Moderate	[32,58]

(*continued on next page*)

Table 3 (*continued*)

Inferential domain	Claim	Minimum evidence threshold	Insufficient evidence	Translational bottleneck	Defensible interpretation	Evidence required for escalation	Current inferential support	References
Risk translation	Food-safety relevance	Edible-tissue detection or crop-associated pathogen/contaminant transfer combined with exposure assessment, bioaccessibility, toxicity, dietary intake, or risk characterization.	Edible-tissue detection alone; MP–metal co-occurrence; pathogen survival on plastic; soil contamination without exposure or risk assessment.	Edible-tissue-to-food-safety gap; contaminant-interaction-to-food-safety gap.	Current evidence supports food-safety concern in specific exposure pathways but rarely supports quantitative human-health risk.	Studies integrating edible-tissue evidence with bioaccessibility, dietary exposure, toxicological thresholds, and risk assessment.	Low–Moderate	[32,54,55,58]
Field translation	Field relevance of mixed polymers	Field, monitoring, archive, sludge-amended, fertilizer-amended, mulch, compost, tilled, rainfall-exposed, or management-linked systems with validated plastic detection and source-pathway attribution.	Pristine single-polymer assays; artificial spiking; water-only sorption tests; laboratory systems without agricultural input pathways.	Single-polymer-to-field-mixture gap; controlled-system-to-agroecosystem gap.	Agricultural soils contain mixed, weathered, management-derived plastic inputs whose distribution depends on source pathway, tillage, fertilizer, biosolid, compost, rainfall, and legacy accumulation.	Integrated field studies linking mixed-polymer exposure with soil function, crop response, contaminant transfer, and management practices.	Strong for exposure; weak–moderate for agronomic effects	[7,35,45,59,60]
Long-term inference	Long-term agronomic impact	Multi-year, multi-season, archive-based, legacy, or repeated field-monitoring evidence showing persistence, fragmentation, redistribution, accumulation, or sustained functional change.	Single-season pot trials; short-term stress markers; field snapshots; legacy contamination without functional or crop-level endpoints.	Short-term-to-long-term gap; legacy-exposure-to-functional-impact gap.	MP can persist, redistribute, fragment, and modify selected soil processes over multi-year or legacy timescales.	Long-term field studies linking legacy MP/NP exposure with soil function, crop productivity, food-safety endpoints, and management outcomes.	Strong for persistence; moderate for functional shifts; weak for productivity impact	[16,35,48,59,60]

Notes: Support levels classify inferential strength rather than study quality and should be interpreted as qualitative categories, not quantitative evidence grades. The classification integrates analytical validity, exposure realism, endpoint validity, temporal support, material realism, and claim scope. The weakest evidence layer constrains each claim: incomplete particle validation limits biological interpretation; low exposure realism limits field translation; endpoint mismatch blocks escalation to agronomic inference; and insufficient temporal or material realism limits long-term or field-level claims. Asterisks (*) identify review-based or secondary sources used for conceptual framing, contextual interpretation, or bottleneck identification; they were not treated as primary evidence for claim-level thresholds.

Abbreviations: ARGs, antibiotic resistance genes; ASVs, amplicon sequence variants; Chao1, Chao1 richness estimator; DGT, diffusive gradients in thin-films; DOC, dissolved organic carbon; HGT, horizontal gene transfer; MDA, malondialdehyde; MPs, microplastics; NH_4^+, ammonium; NO_3^-, nitrate; NPs, nanoplastics; PCoA, principal coordinate analysis; ROS, reactive oxygen species; Shannon, Shannon diversity index; SMX, sulfamethoxazole; SOC, soil organic carbon; SOM, soil organic matter; SPAD, Soil Plant Analysis Development chlorophyll index.

cropland, farmland, rhizosphere, or soil–plant context; and endpoints were relevant to at least one level of the soil–microbiome–plant continuum.

Studies were not selected to provide exhaustive coverage of all records in the bibliometric corpus. The selection was not randomized, blinded, or conducted as independent duplicate screening and does not claim statistical representativeness. To reduce selection bias, studies were selected according to predefined functional and methodological criteria rather than according to the direction, magnitude, or statistical significance of reported effects.

Studies were excluded from Tables 1 and 2 when they focused solely on aquatic systems, marine pollution, human dietary exposure modeling, life-cycle assessment, polymer degradation outside soil–plant contexts, or analytical method development without soil, microbial, plant, contaminant-transfer, tissue-level, biomass, yield-related, or agronomic endpoints. Method-oriented sources were used only when they informed analytical constraints relevant to MP/NP detection, extraction, or interpretation and were not counted as empirical soil–-plant response studies.

Consequently, Tables 1 and 2 should be interpreted as representative synthesis tables organized by functional domain, polymer type, exposure system, endpoint class, and inferential constraint. They show how different types of evidence support different levels of claim, rather than providing a complete census of all eligible empirical studies in the bibliometric corpus.

2.3.3. Evidence extraction

For each selected study, information was extracted across the domains defined in the inclusion criteria (Section 2.3.2), with additional specification of analytical methods for polymer identification, particle quantification, and tissue-level detection when reported. Specifically, extracted information included polymer type, particle morphology, particle size or size range, exposure dose, exposure metric, experimental system, soil or growth matrix, crop or plant species, exposure duration, analytical method, soil physical endpoints, biogeochemical endpoints, microbial endpoints, plant physiological endpoints, biomass or yield-related endpoints, tissue-level particle detection, and contaminant-transfer endpoints.

2.3.4. Functional and inferential classification

Extracted evidence was classified into functional domains corresponding to the main levels of the soil-microbiome-plant system. Soil physical-hydraulic responses included aggregation, porosity, bulk density, water retention, and hydraulic conductivity. Biogeochemical responses included pH, dissolved organic carbon, soil organic carbon, nitrogen availability, nutrient cycling, enzyme activity, and contaminant mobility. Rhizosphere and microbiome responses included microbial diversity, community composition, functional genes, enzyme activity, microbial networks, and plastisphere-related responses. Plant and tissue-level responses included germination, root architecture, nutrient uptake, chlorophyll or SPAD index, oxidative stress indicators, biomass, yield-related variables, and tissue-level detection of particles or associated contaminants.

For inferential classification, endpoints were grouped according to the type of claim they could support: contamination occurrence, mechanistic response, soil functional alteration, microbial functional response, plant physiological response, crop performance, contaminant transfer, or food-safety relevance.

2.3.5. Exposure realism and comparability

Exposure conditions were classified to evaluate their comparability with agronomic soil-plant systems. Because MP/NP studies report exposure using different metrics, including % w/w, mg kg^{-1}, mg L^{-1}, particles kg^{-1}, and particles mL^{-1}, direct conversion across metrics was not attempted unless particle density, particle size distribution, and polymer mass information were available.

Field-aligned exposure was assigned when the exposure metric, matrix, and duration were within one order of magnitude of reported agricultural field concentrations. This threshold was used as a pragmatic interpretive screening criterion because cross-study dose harmonization remains constrained by incompatible mass-, count-, and volume-based metrics. It should not be interpreted as a universal environmental-realism standard across polymers, soil matrices, dose units, or exposure histories.

2.3.6. Particle-size definitions

For classification purposes within this synthesis, microplastics were defined as solid polymer particles ranging from 1 μm to 5 mm in size. Nanoplastics were operationally defined as particles smaller than 1 μm (<1 μm), following the criterion used in the soil-plant studies included in the analyzed literature. It is acknowledged that some reference frameworks and specific studies apply a more restrictive threshold (<100 nm); however, this delimitation was not adopted in the present review. Claims involving NPs should therefore be interpreted according to the operational size definition used here, not as claims restricted to engineered or environmental particles below 100 nm. These definitions were used exclusively for classification and evidence organization during the synthesis process.

2.4. Agronomic inference framework

2.4.1. Framework construction

The agronomic inference framework was developed from recurrent methodological and interpretive constraints identified during the extraction and classification of the selected studies. It is proposed as an interpretive claim-alignment tool rather than as a validated scoring system. These constraints were structured into three primary inferential filters: analytical validity, exposure realism, and endpoint validity. Analytical validity comprised methodological attributes related to polymer identification, particle-size detection, recovery efficiency, matrix-interference control, and contamination control during sampling and analysis. Exposure realism referred to the extent to which exposure systems reflected agricultural soil–crop conditions, considering soil matrix characteristics, texture, organic matter content, pH, water regime, particle aging, polymer mixtures, dose comparability, and exposure duration. Endpoint validity referred to whether the measured outcome corresponded to the claim being advanced, including soil physical or biogeochemical function, microbial functional response, plant physiological response, crop performance, contaminant transfer, edible-tissue relevance, and field-level agronomic interpretation. These primary filters were subsequently linked to claim-specific thresholds. Temporal structure, integrated soil–microbiome–plant design, material realism, and claim scope were treated as higher-order design dimensions that constrained the maximum defensible interpretation rather than as substitutes for analytical validity, exposure realism, or endpoint validity.

2.4.2. Experimental-system levels

The extracted evidence was organized into six experimental-system levels according to study configuration and exposure context. The first level corresponded to analytical detection studies reporting MP/NP occurrence in soils, amendments, irrigation water, fertilizers, or plant-associated matrices. The second level included hydroponic and in vitro exposure systems conducted under solution-based conditions lacking soil structure. The third level comprised short-term soil microcosm studies performed under controlled conditions with limited experimental duration and simplified environmental complexity. The fourth level included pot experiments conducted with agricultural soil matrices under controlled or semi-controlled conditions. The fifth level corresponded to full crop-cycle semi-field or field experiments assessing plant performance throughout complete growth periods under soil-based exposure conditions. The sixth level included multi-season or

multi-site field studies involving repeated measurements or spatial replication across contrasting soil–crop systems.

These six levels were used to code the experimental configuration and exposure context of each study. They describe where and under what conditions evidence was generated, rather than the inferential status of the claim itself. Claim interpretation was evaluated separately using the analytical-validity, exposure-realism, endpoint-validity, and claim-level criteria defined in the framework. Therefore, the experimental-system level was treated as contextual metadata for inference, not as a cumulative quality score or as a direct measure of agronomic claim strength.

2.4.3. Claim-level inference criteria

Claim-level inference criteria were established to define the minimum evidentiary requirements for supporting recurrent agronomic claims reported in MP/NP soil-plant studies. These criteria were applied to ensure consistency between the scope of interpretation and the empirical evidence available in each study.

Claims of plant internalization were considered supported only when particle detection within internal plant tissues was analytically validated and accompanied by contamination control during sample preparation and analysis. Claims regarding yield reduction or productivity loss required the measurement of final biomass, yield, harvestable tissue, or crop-performance variables across biologically relevant growth periods. Microbial functional-response claims were assigned only when microbial endpoints included activity-, flux-, or process-linked measurements, such as enzyme activity, respiration, nutrient cycling rates, gas fluxes, microcalorimetry, or measured metabolic activity. Functional genes, predicted pathways, metabolic profiles, and network metrics were coded as functional-potential evidence unless linked to measured activity or process-rate endpoints.

Similarly, claims concerning contaminant-vector effects required same-system evidence linking polymer–contaminant interaction, mobility or bioavailability, and biological uptake, transfer, or tissue burden. Claims of food-safety relevance required edible-compartment evidence linked to exposure-oriented assessment, including edible-tissue burden and, where applicable, surface–interior distinction, bioaccessibility, dietary exposure, contaminant or additive context, and risk-relevant interpretation. Claims referring to field-level agronomic inference required analytically defensible particle evidence, realistic soil matrices, field-aligned or explicitly justified exposure conditions, crop-cycle duration, and endpoints matched to the claim being advanced.

3. Results and discussion

3.1. Bibliometric evidence of a translational imbalance

The bibliometric analysis was used to diagnose how research on microplastics and nanoplastics in agricultural soil–plant systems developed between 2015 and 2025 and to evaluate the extent to which the structure of the field is aligned with agronomic inference. In this section, bibliometric outputs are interpreted as indicators of disciplinary orientation, thematic development, and geographical concentration. They are not treated as stand-alone evidence of soil, biological, toxicological, or agronomic effects. Instead, they are used to contextualize how the literature is organized in relation to the translational gap between mechanistic evidence and agronomic inference.

3.1.1. Growth, disciplinary distribution, and corpus structure

The final corpus comprises 1815 records published between 2015 and 2025. Original research articles dominate the corpus with 1410 records (77.7%), followed by review articles (246 records; 13.6%) and book chapters (108 records; 6.0%) (Fig. 1A). This article-dominated structure is consistent with a field strongly oriented toward empirical data generation rather than consolidated secondary synthesis.

Annual publication output increased markedly during the study period, with the highest number of documents recorded in 2025 (Fig. 1D). The fitted polynomial trend represents only a descriptive illustration of publication growth; it does not constitute a predictive model. Older annual cohorts have accumulated more citations than recent cohorts due to their longer exposure time. Therefore, publication output is more informative than raw citation accumulation for evaluating the expansion of the field. The disciplinary distribution reveals an asymmetry among Scopus subject areas. Environmental Science accounts for 1414 classifications (45.7%), whereas Agricultural and Biological Sciences accounts for 386 classifications (12.5%), a difference of approximately 3.6-fold (Fig. 1C). Other areas associated with analytical, chemical, or technical dimensions (Chemistry, Pharmacology, Toxicology and Pharmaceutics, and Engineering) also contribute to the corpus (Fig. 1C). This disciplinary profile reflects that MPs/NPs research in agricultural soils centers primarily on environmental characterization, contaminant analysis, and risk-oriented characterization, with comparatively lower integration into agronomic and crop-production frameworks.

This distribution does not diminish the value of the existing literature. Environmental and analytical studies provide the foundation for identifying particle occurrence, polymer types, and exposure pathways. However, the bibliometric dominance of environmental and analytical categories indicates that the field prioritizes detection and characterization over field-level agronomic inference. This result constitutes the first dimension of the translational imbalance identified in this review.

The Supplementary Material (Figs. S1 and S2) contains author- and institution-level collaboration networks and institution–keyword–country coupling analyses.

3.1.2. Semantic evolution and thematic displacement

The frequency distribution of normalized Author Keywords shows a hierarchical thematic structure within the research field. The most prominent terms “microplastics”, “agricultural soil”, “soil”, and “nanoplastic” dominate the keyword landscape (Fig. 2A), indicating that the corpus is primarily framed within agricultural soil-plant contexts. However, keyword frequency alone does not indicate functional integration; rather, it identifies the predominant descriptors used to delimit the field.

The co-occurrence network and temporal heatmap provide a complementary representation of thematic organization and evolution (Fig. 2A and B). Terms associated with environmental occurrence and exposure matrices “agricultural soil”, “sewage sludge”, and “biosolids” were most prominent during the earlier phase of the analyzed period (2015–2019), reflecting an initial emphasis on occurrence, input pathways, and contamination sources. Physicochemical terms such as “heavy metals”, “adsorption”, and “cadmium” maintained strong connectivity with the central microplastics node, consistent with sustained attention to contaminant interactions and vector-related processes.

Biological and mechanistic terms “microbial community”, “phytotoxicity”, “oxidative stress”, “metabolomics”, and “rhizosphere” increased in prominence from 2021 onward, with peak intensity in 2024–2025 (Fig. 2B), reflecting a thematic shift toward biological-response and process-oriented research. In contrast, at the applied occurrence threshold, terms directly associated with agronomic endpoints “yield”, “crop performance”, “edible tissues”, and “field validation” do not appear among the frequent keywords in Fig. 2B, indicating limited integration of agronomic dimensions within the dominant semantic structure.

Nanoplastic-related terms display later emergence and lower temporal intensity than those associated with microplastics. In the co-occurrence network (Fig. 2A), “nanoplastic” appears as a smaller node connected to the central core, consistent with comparatively lower thematic consolidation during the analyzed period. The methodological implications of this asymmetry are examined in later sections in relation to particle detectability and evidence-level interpretation.

The keyword structure indicates a transition from environmental

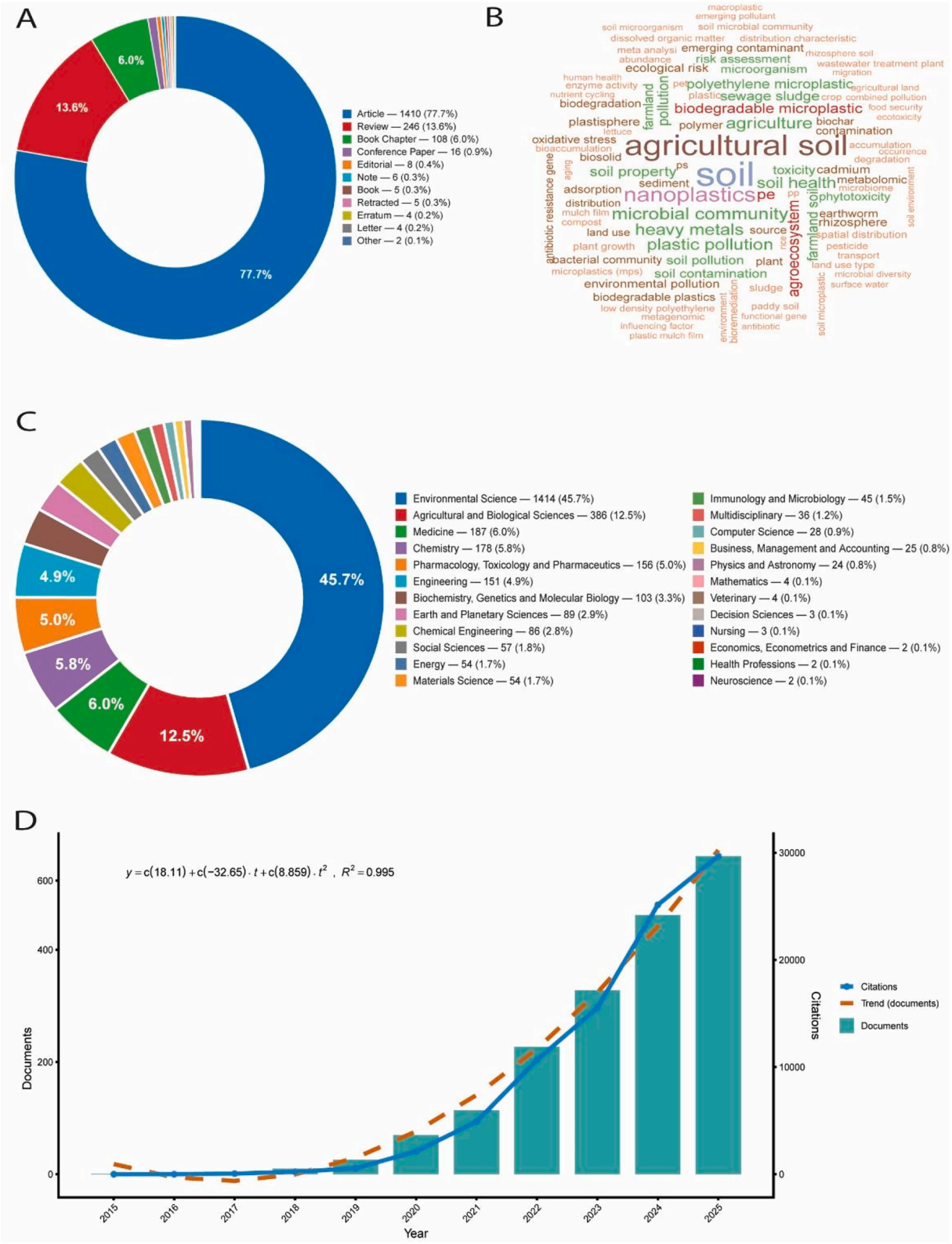

Fig. 1. Corpus composition, disciplinary structure, keyword frequency, and temporal dynamics of research on microplastics and nanoplastics in agricultural soil-plant systems (2015–2025; n = 1815). (A) Document types within the final corpus. (B) Normalized frequency of Author Keywords, term size represents relative frequency, not co-occurrence strength. (C) Scopus subject areas reported as multi-indexed classifications. (D) Documents published per year and accumulated citations by annual cohort. Polynomial fits and corresponding R^2 values are shown as descriptive guides.

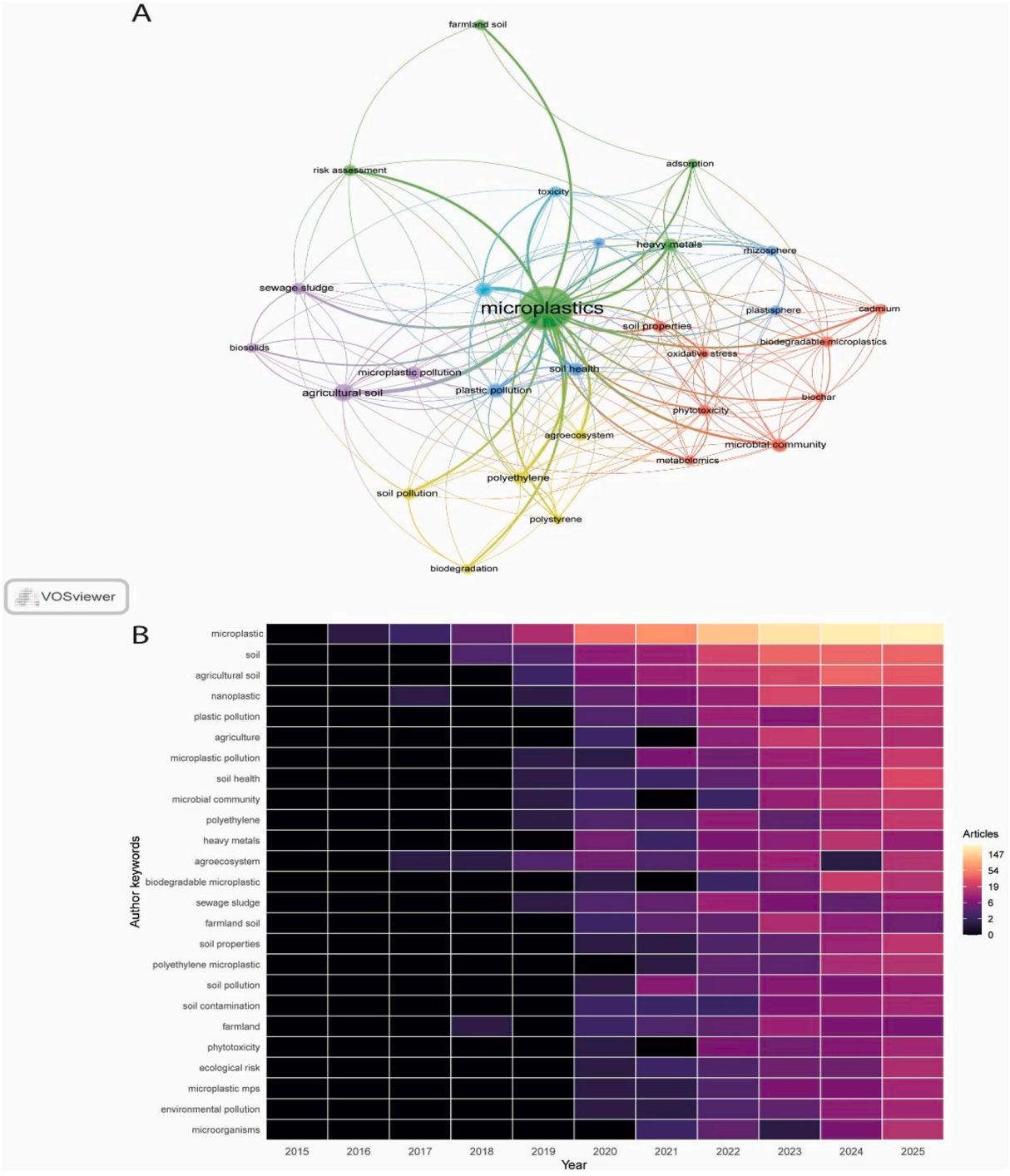

Fig. 2. Author Keyword co-occurrence structure and temporal evolution of dominant research topics in microplastics and nanoplastics in agricultural soil-plant literature (2015–2025). (A) Co-occurrence network of normalized Author Keyword terms generated in VOSviewer using full counting and association-strength normalization, with a minimum threshold of 20 occurrences per term. Node size represents keyword frequency, link thickness represents co-occurrence strength, and colors indicate keyword clusters. (B) Temporal heatmap of normalized Author Keyword terms from 2015 to 2025, where color intensity represents the number of records per year containing each term.

detection and occurrence-oriented research toward biological and mechanistic interpretation. This transition remains incomplete, as themes directly linked to realistic agronomic performance and field-level validation show limited integration within the dominant semantic structure. This pattern supports the interpretive framework of this review: mechanistic development advanced more rapidly than agronomic translational integration during the 2015–2025 period.

3.1.3. Geographical concentration and limits to global inference

Scientific production exhibits geographical concentration within a limited number of countries (Fig. 3A and B). China contributed 319 documents (17.6%), the United States 108 (6.0%), and the United Kingdom 94 (5.2%). These three countries account for 28.7% of the corpus. The 12 most productive countries contributed 848 documents (46.7% of the total corpus) (Fig. 3B).

This distribution identifies the national contexts from which a substantial proportion of indexed evidence originates. The country-level co-authorship network indicates international collaboration among highly productive countries, particularly across East Asia, North America, Europe, and Oceania (Fig. 3A). The chord diagram indicates that collaboration intensity is concentrated among the leading publication-producing countries (Fig. 3B). Because link weights are determined by publication volume under full-counting assignment, these connections reflect absolute co-authorship frequency, not normalized collaborative affinity or methodological convergence.

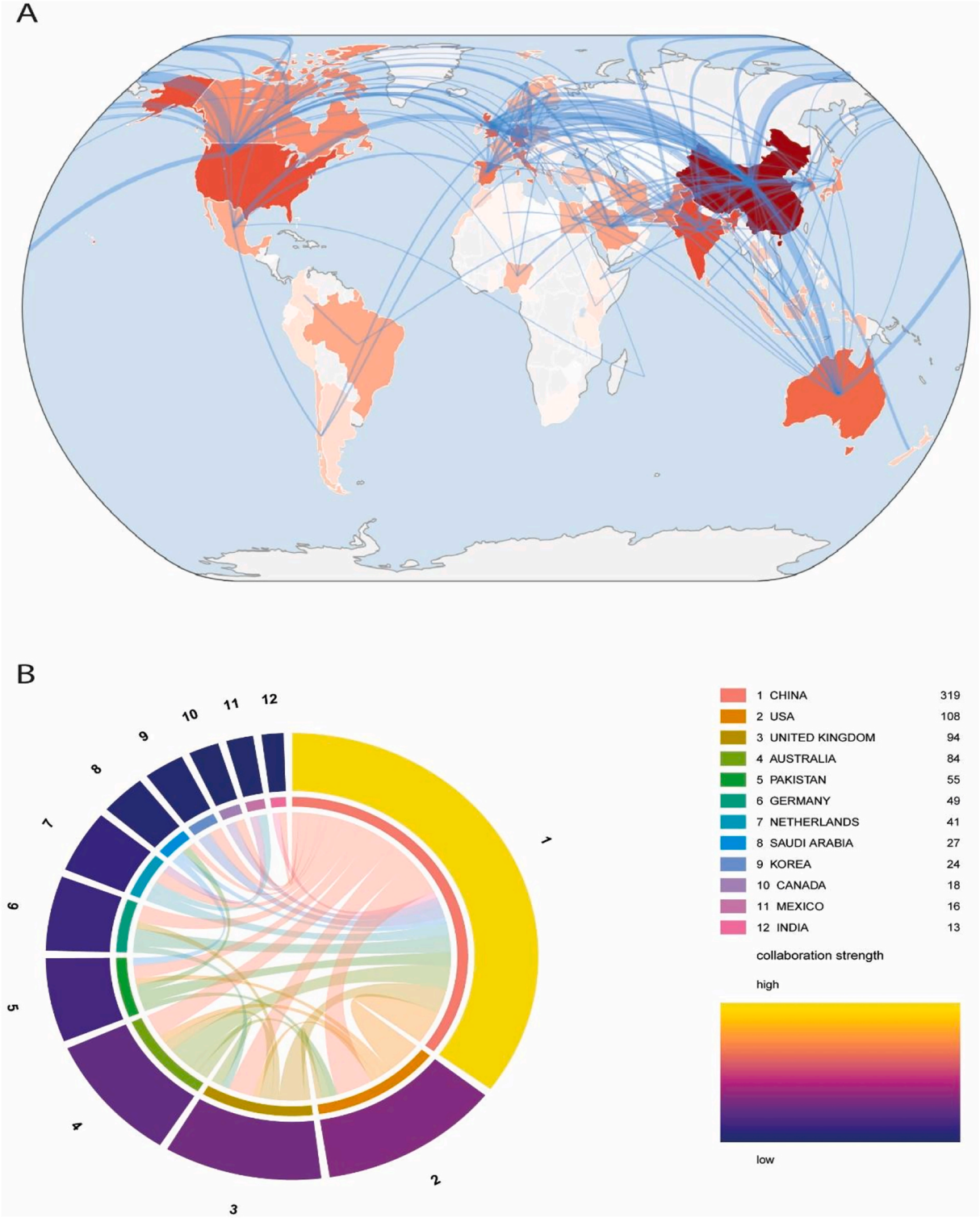

Fig. 3. Geographical distribution of scientific production and international country-level co-authorship in microplastics and nanoplastics research in agricultural soil-plant systems (2015–2025).
(A) Color intensity represents scientific production by author-affiliation country, with arcs indicating country–country co-authorship links derived from co-authored documents, and (B) Chord diagram of the 12 most productive countries, where sector size represents publication output and chords represent co-authored documents between country pairs; link strength should be interpreted relative to publication volume rather than as normalized collaborative affinity.

The geographical structure of the corpus can limit the generalizability of agronomic inference because responses to MPs/NPs in soil–plant systems depend on soil texture, mineralogical composition, organic matter content, pH, hydrological regime, crop type, plastic input pathway, and management practices. Evidence generated within a limited set of national or production contexts requires validation across underrepresented agroecological systems, including tropical, arid, saline, volcanic, and highly weathered soils, as well as smallholder production systems, intensive plasticulture, biosolid- or compost-amended soils, and wastewater-irrigated agricultural systems.

The geographical pattern adds an agroecological dimension to the translational imbalance identified in this review. The limitation extends beyond thematic separation between detection-oriented and function-oriented research and includes restricted environmental representativeness across global agricultural systems. Agronomic inference requires validation across contrasting soil classes, climatic conditions, crop systems, and management regimes before mechanistic observations can support broader field-level interpretation.

These bibliometric patterns indicate that MP/NP research in agricultural soil–plant systems has developed substantial capacity for particle detection, environmental characterization, and risk-oriented characterization. Integration among particle identification, realistic soil exposure, biological mechanisms, and crop-level agronomic outcomes remains limited. This contextualizes the mechanistic synthesis that follows: the evidence summarized in the next section should be read not as a comprehensive account of all possible MP/NP effects, but as a structured organization of current mechanistic understanding, with explicit attention to the analytical, exposure, and endpoint constraints that limit its agronomic reach.

3.2. Mechanistic evidence across soil–microbiome–plant systems

The edaphic, microbial, plant-level, tissue-level, and contaminant-interaction evidence summarized in Tables 1 and 2 indicates that responses to MPs/NPs in soil–plant systems are strongly context-dependent. Under the interpretive framework developed in this review, this evidence supports the organization of MP/NP effects into six mechanistic domains: soil physical-hydraulic alteration, biogeochemical responses, rhizosphere microbiome restructuring, plant physiological response, particle internalization and tissue-level evidence, and mixed particle-chemical exposure. The agronomic interpretability of each domain depends on analytical validity, exposure realism, and endpoint validity.

3.2.1. Soil physical-hydraulic responses

Evidence summarized in Table 1 indicates that MPs can alter soil physical-hydraulic behavior. Reported responses include changes in bulk density, pore connectivity, aggregation, infiltration, water retention, and particle redistribution. These responses are not intrinsic properties of plastic particles as a uniform contaminant class; they arise from interactions among polymer identity, particle morphology, exposure concentration, soil texture, pore-size distribution, hydrological regime, and management history. Controlled soil studies indicate that plastic particles can modify soil structural organization under specific exposure conditions rather than acting solely as passive inclusions within the soil matrix [61].

Hydraulic responses are particularly sensitive to soil matrix properties. In loess soils, MP exposure altered unsaturated infiltration and water-retention behavior, with particle size and concentration influencing the magnitude of the response [62]. This evidence supports a mechanistic relationship between particle characteristics and soil water movement, but it does not support extrapolation across soil types without accounting for texture, aggregation status, pore architecture, antecedent moisture conditions, and hydraulic boundary conditions. Agricultural management further influences particle distribution within the soil profile. Tillage can redistribute particles vertically and horizontally, whereas migration studies indicate that particle transport depends on both particle characteristics and soil transport processes [7,63].

Long-term field observations indicate temporal persistence and redistribution of plastic particles in agricultural topsoils over decadal timescales, supporting the interpretation that MP exposure can represent a dynamic soil process rather than a static surface accumulation phenomenon [35,59]. In legacy mulching systems containing PE and LDPE residues, reduced aggregate stability and lower hydraulic conductivity have been reported relative to non-mulched controls, supporting the relevance of chronic plastic inputs for soil structural behavior [26]. Biodegradable and mulch-derived polymers should not be considered physically neutral solely because they are designed to degrade. Their effects depend on residue size, degradation dynamics, polymer composition, soil conditions, and management history [43,45].

A major limitation for agronomic inference is the discrepancy between controlled experimental exposure and field exposure. Many controlled studies use concentrations expressed as % w/w, whereas field burdens are commonly reported using mass- or particle-based units such as mg kg^{-1} or particles kg^{-1}. This difference creates a dose-realism and unit-comparability gap that constrains direct translation of experimental findings to agricultural systems. The available evidence supports the mechanistic plausibility of MP-induced physical-hydraulic alteration but does not support generalized claims of field-level soil degradation. Stronger agronomic inference requires validation across environmentally realistic exposure levels, contrasting soil textures, complete crop cycles, and management-specific field conditions.

3.2.2. Biogeochemical responses and contaminant mobility

Evidence summarized in Table 1 indicates that MP/NP exposure can modify soil biogeochemical functioning through changes in carbon and nitrogen cycling, pH-sensitive reactions, nutrient availability, enzyme activity, and contaminant behavior. These responses are agronomically relevant because soil fertility depends on the coupling among organic matter dynamics, microbial activity, nutrient mineralization, and plant nutrient uptake. However, biogeochemical responses remain context-dependent and vary according to polymer identity, particle aging, exposure dose, soil matrix properties, redox conditions, and co-contaminant profiles.

Nitrogen- and carbon-related parameters illustrate this context dependence. MP exposure has been associated with changes in available nitrogen pools, nitrogen storage, nitrogen emissions, ammonia volatilization, and soil health indicators, although the magnitude and direction of these responses vary across soil systems and exposure conditions [22,64]. Polymer-specific effects have also been reported. For example, PA (nylon) fibers in Andisol soils were associated with increased NH_4^+ availability, indicating that polymer identity can influence nitrogen dynamics [22]. Carbon-related responses are similarly mediated by soil structure and microbial processing. Alterations in organic carbon mineralization, aggregate distribution, and the relative contribution of plant-derived and microbial-derived carbon have been reported, linking physical soil perturbation with carbon stabilization and turnover pathways [48,65].

Hydrological and rhizosphere conditions further influence biogeochemical responses. In flooded rice systems, MP exposure altered nutrient dynamics at the soil-water interface, indicating that redox-sensitive environments can regulate MP effects on nutrient availability and transformation [49]. In rice rhizosphere soils, PE, PLA, and aged PLA modified physicochemical properties and microbial diversity, indicating that polymer identity and aging status can influence chemical and biological responses simultaneously [66]. Face mask-derived MPs have also been associated with changes in mineralizable nitrogen, soil organic matter, and biological soil-quality indicators, indicating that polymer-derived residues can affect multiple components of soil functioning rather than a single nutrient pool [28].

Contaminant mobility represents a related but distinct mechanism.

Studies focused on metals indicate that MPs can modify heavy metal mobility, bioavailability, uptake, or toxicity, although these responses depend on polymer chemistry, particle size, soil properties, crop species, and contaminant speciation. Consequently, evidence derived from lettuce, radish, carrot, cadmium-contaminated soils, and metal-stressed plant systems should be interpreted within their respective experimental contexts because these studies differ in crop system, polymer type, soil matrix, and endpoint structure [6,32,54,67,68]. Current evidence supports contaminant-interaction plausibility but does not support a universal prediction of enhanced metal transfer.

Organic contaminants introduce an additional layer of complexity. MP exposure has been associated with altered herbicide efficacy, sulfamethoxazole bioavailability, and perfluorooctanoic acid adsorption-desorption behavior, indicating that plastic particles can influence contaminant fate through sorption, desorption, or co-sorption processes [17,33,69,70]. A defensible vector-effect claim requires same-system evidence linking: (i) polymer presence within the exposure matrix, (ii) contaminant sorption, mobility, or bioavailability, and (iii) biological uptake, transfer, or tissue burden within the exposed organism or crop compartment. Evidence restricted to sorption, desorption, mobility, or field co-occurrence alone does not establish a vector effect; correlation between MPs and contaminants in soil does not constitute MP-driven uptake without direct transfer measurements.

Evidence currently available supports MP/NP involvement in biogeochemical perturbation and contaminant-interaction mechanisms, although these responses remain conditional and system-specific. Agronomic inference requires demonstrating that alterations in nutrient cycling or contaminant mobility translate into measurable changes in soil functioning, plant nutrient uptake, or crop-relevant outcomes under realistic exposure conditions. These responses connect directly with rhizosphere microbiome processes, where chemical perturbations may be amplified, attenuated, or redirected through microbial functional responses.

3.2.3. *Rhizosphere microbiome responses and context-dependent functional shifts*

The microbial evidence summarized in Table 1 associates MP/NP exposure with changes in rhizosphere community structure, enzyme activity, functional gene profiles, and microbial metabolic processes. These responses vary according to polymer identity, particle size, aging status, soil pH, organic matter content, crop species, exposure duration, and co-contaminant presence. For agronomic interpretation, a critical distinction concerns whether the reported responses correspond to taxonomic restructuring, functional modification, or both.

Polymer-specific studies provide examples of this context dependence. In rice rhizosphere soils, PE, PLA, and aged PLA modified physicochemical properties and microbial diversity, linking microbial responses to both polymer characteristics and local soil conditions [66]. Face mask-derived MPs were associated with changes in biological soil properties and soil-quality indicators, indicating that polymer-derived residues may produce distinct microbial responses that cannot be represented by a single MP exposure category [28]. In mollisols, soil pH regulated catalase activity and bacterial community responses following MP exposure, indicating the influence of background soil chemistry on microbial sensitivity and enzyme-level processes [71].

Functional endpoints provide a stronger basis for ecological interpretation than taxonomic metrics alone. Comparative assessments using isothermal microcalorimetry and respirometry detected changes in microbial activity that were not captured exclusively through community composition analyses [29]. Changes in Chao1 richness, Shannon diversity, ASVs, or community composition document microbial restructuring, but they do not directly establish alterations in nutrient cycling, disease suppression, contaminant transformation, or soil functional performance. Functional inference is strongest when taxonomic or omics-based signals are linked to activity- or process-oriented endpoints, including enzyme activity, respiration, heat-flow measurements, nutrient-cycling rates, or measured metabolic activity. Functional genes, metabolic pathways, and microbial interaction networks support functional-potential or pathway-level interpretation unless they are connected to measured process rates.

Microbial responses are further conditioned by co-contaminants and redox environments. Combined exposure to nanoplastics and cadmium altered rhizosphere bacterial communities associated with *Sedum alfredii*, indicating that community restructuring may result from polymer–metal interactions rather than from plastic exposure alone [72]. Polyamide MPs combined with antimicrobials in reclaimed water modified lettuce-associated soil bacterial communities and antibiotic-resistance-related responses; however, ARG-related signals do not constitute evidence of horizontal gene transfer unless direct transfer events are documented [41]. In paddy soils, nanoplastic exposure was associated with increased methane production and shifts toward Methanocella-dominated communities, linking anaerobic conditions with modifications in carbon-cycling processes [73].

The available evidence documents context-dependent microbial restructuring and, in selected systems, microbial functional responses following MP/NP exposure. However, current evidence does not support a consistent positive or negative effect across soil microbial communities. Taxonomic changes alone are therefore insufficient to support functional claims unless they are linked to measured activity, fluxes, or process-rate endpoints.

3.2.4. *Plant physiological and productivity-related responses*

The plant-level evidence summarized in Table 2 associates MP/NP exposure with responses in germination, root architecture, photosynthetic traits, chlorophyll-related indices, oxidative stress markers, nutrient uptake, biomass accumulation, and crop-performance endpoints. These variables differ substantially in inferential strength. Physiological and molecular indicators, including SPAD, MDA, proline, chlorophyll content, antioxidant activity, root length, and gene-expression responses, document stress responses, acclimation processes, or pathway-level alterations. However, these endpoints do not constitute evidence of yield reduction unless accompanied by crop-performance measurements obtained over biologically relevant growth periods.

Plant responses vary according to crop species, exposure conditions, and soil context. Evidence from edible crops exposed to environmentally relevant MP concentrations indicates that growth and stress-related processes are mediated by species-specific characteristics, including root architecture, transpiration demand, nutrient-acquisition strategy, and sensitivity to oxidative stress [52]. Consequently, responses observed in a particular crop or exposure system cannot be extrapolated directly to other crop species or production systems. This distinction is particularly important when separating soil-mediated plant responses from direct particle–plant interactions.

Studies conducted in root and leafy vegetables show that plant responses frequently emerge from combined soil–polymer–contaminant interactions rather than from polymer exposure alone. PET exposure has been associated with changes in radish and carrot growth, nutrient uptake, and physiological stress responses [32]. In lettuce systems, MP-associated heavy-metal uptake links plant responses to contaminant dynamics, whereas studies conducted in metal-contaminated soils indicate that plant responses may be influenced simultaneously by changes in contaminant availability and soil microbial communities [6,68]. These experimental systems differ in crop species, polymer type, soil matrix, contaminant chemistry, and endpoint structure and should not be interpreted as a single exposure model. Comparable limitations apply when comparing hydroponic studies evaluating PS-NP effects on soybean with field-based studies assessing PE/LDPE residues under long-term mulching systems [23,26].

Evidence obtained across contrasting cropping systems further indicates that plant responses are conditioned by broader edaphic and management factors. Soil amendments, cadmium co-exposure, and

interactions with arbuscular mycorrhizal fungi modify plant responses to MP/NP exposure, indicating that polymer exposure represents one component within a broader soil–plant interaction framework [67,74–76]. In white lupine, alterations in plant parameters occurred without corresponding changes in soil enzyme activity, indicating partial decoupling between plant-level responses and soil functional responses under specific exposure conditions [31].

Synthesis of the representative evidence summarized in Tables 1 and 2 indicates that evidence related to crop productivity remains less developed than evidence describing physiological responses. While some studies report biomass accumulation, emergence, fruiting, or yield-related endpoints, a larger proportion focuses on early growth responses, stress indicators, or molecular markers. For example, PVC exposure reduced growth in peanut under controlled pot conditions, whereas PLA/PBAT exposure produced dose-dependent responses in maize [24,44]. This distinction has direct implications for agronomic inference. Changes in SPAD, MDA, proline, chlorophyll content, root length, or transporter-gene expression indicate biological responses but do not establish reductions in productivity. Endpoints such as mature biomass, fruit number, fruit weight, grain yield, harvestable tissue quality, and field-level crop establishment provide stronger agronomic relevance because they are directly linked to crop performance.

Current evidence supports mechanistic associations between MP/NP exposure and plant physiological or growth-related responses. In contrast, claims regarding productivity loss require crop-performance endpoints measured under soil-based systems, field-aligned exposure conditions, or complete crop-cycle experiments. This distinction separates evidence of biological response from evidence supporting agronomic inference and provides the transition to particle internalization and tissue-level detection, where the focus shifts from whole-plant responses to the pathways through which particles may enter plant tissues.

3.2.5. *Particle internalization and tissue-level evidence*

The tissue-level evidence summarized in Table 2 indicates that particle internalization presents both analytical and inferential challenges. Reports describing particles on root surfaces, within the rhizosphere, or associated with plant tissues do not constitute confirmation of internalization. Likewise, tissue-associated signals do not demonstrate translocation to edible organs. Claims of particle internalization require validated tissue-level localization, contamination control procedures, and analytical methods capable of distinguishing internalized particles from external adherence.

Studies conducted under controlled exposure systems indicate that submicrometric plastic particles can enter crop roots through crack-entry pathways associated with lateral root emergence sites, providing a potential mechanism for root-level uptake [77]. However, this pathway cannot be extrapolated across polymer types, crop species, soil matrices, or plant organs without particle-specific localization and exposure validation. Evidence synthesized for microplastics and nanoplastics in agricultural products indicates that particle behavior, plant interactions, and tissue association depend on particle size, polymer chemistry, tissue type, and analytical detection strategy [78,79].

Analytical reliability remains central to the interpretation of tissue-level evidence because internalization requires localization rather than detection alone. Matrix interference, tissue autofluorescence, airborne contamination, extraction efficiency, and particle-size detection limits can influence the interpretation of MP/NP signals in plant tissues and associated soil matrices [80–82]. Method-validation studies conducted in organic fertilizers and compost-amended soils further indicate that matrix composition and sample preparation affect particle recovery and identification [36,83]. Consequently, tissue-level observations should be interpreted together with analytical performance metrics and contamination-control procedures.

For agronomic and food-safety interpretation, a distinction is required among root-surface association, tissue internalization, translocation, accumulation in edible organs, and exposure relevance. Root-associated particles may influence root physiology or nutrient acquisition but do not imply consumer exposure. Tissue-level internalization supports mechanistic interpretation of particle uptake pathways; however, food-safety relevance requires validated detection in edible tissues together with exposure-oriented assessment. In the absence of such evidence, particle internalization should be interpreted as a documented mechanism under specific analytical and experimental conditions rather than as generalized evidence of edible-tissue accumulation or formal human-health risk.

The available evidence therefore supports the occurrence of particle uptake pathways in selected experimental systems, while the extent of translocation, accumulation in edible tissues, and implications for food-safety assessment remain dependent on analytical validation, tissue-specific localization, and exposure context. These considerations set the stage for scenarios that move beyond single-polymer exposure.

3.2.6. *Mixed polymers, additives, and co-contaminants*

The evidence summarized in Tables 1 and 2 indicates that agricultural MP/NP exposure occurs within complex particle–chemical mixtures rather than as isolated contact with pristine single polymers. Controlled experiments commonly employ well-characterized polymers to isolate specific mechanisms; however, agricultural soils receive heterogeneous inputs of mixed polymers, weathered particles, additives, plasticizers, and co-occurring contaminants through mulch films, geotextiles, sewage sludge, biosolids, compost, organic fertilizers, wastewater irrigation, and other management-related pathways. This contrast between controlled exposure systems and agricultural exposure scenarios constrains direct extrapolation of experimental outcomes to field conditions.

Field observations and source-oriented studies document the diversity of agricultural plastic inputs. Macroplastics and microplastics have been detected in agricultural soils, and plastic residues can persist or redistribute decades after sewage-sludge application [35,37]. Long-term wastewater irrigation, biosolid amendment, municipal solid waste compost, biowaste compost, and compost-amended soils represent additional pathways for plastic-particle introduction into agricultural systems [36,38–40,84]. These exposure pathways generate particle mixtures that differ in polymer composition, particle size distribution, aging status, and associated contaminant load.

Particle aging introduces further variability. Weathered particles can exhibit altered surface chemistry, increased roughness, fragmentation-derived size distributions, modified functional-group composition, and altered sorption behavior. These properties influence interactions with soil aggregates, microbial communities, root surfaces, nutrients, and co-occurring contaminants. Commercial biodegradable mulch films also represent chemically complex exposure sources rather than uniform degradable materials. Evaluations of biodegradable agricultural polymers in terrestrial systems report changes in soil properties and plant responses associated with mulch degradation products [43,45,85]. Consequently, biodegradable polymers require assessment based on degradation products, residue persistence, and soil interactions rather than classification according to intended degradability [86,87].

Co-contaminants introduce additional exposure pathways. MP presence has been associated with changes in herbicide performance, sulfamethoxazole bioavailability, and perfluorooctanoic acid adsorption–desorption dynamics, indicating that plastic particles can participate in contaminant-partitioning processes through sorption, desorption, and co-sorption mechanisms [17,33,69]. Polyamide MPs combined with antimicrobial residues in reclaimed irrigation water modified lettuce-associated soil bacterial communities, indicating that

irrigation-water chemistry and contaminant composition influence polymer-related responses [41]. Evidence of sorption or contaminant redistribution alone does not establish biological transfer, crop toxicity, or food-safety relevance; these outcomes require direct demonstration within the same exposure system.

Metal-associated responses also vary according to exposure context. MP exposure has been associated with altered cadmium behavior, while polymer identity, particle size, soil chemistry, and contaminant speciation influence uptake and exposure pathways [67]. Studies involving lettuce, spinach, industrial hemp, and metal-contaminated soils report increases, decreases, or redistribution of metal exposure depending on the experimental system and environmental conditions [6,88,89]. These outcomes indicate that MP–metal interactions are conditional processes governed by system-specific physicochemical and biological factors.

Agricultural MP/NP exposure therefore encompasses interacting particles, degradation products, additives, weathering-derived residues, and co-occurring contaminants operating across soil, microbiome, plant, and contaminant compartments. Single-polymer experiments remain essential for mechanistic resolution, but no single mechanistic pathway adequately captures MP/NP behavior under agricultural conditions. Agronomic interpretation therefore requires integrated evaluation of analytical reliability, exposure realism, material complexity, mechanistic evidence, and claim-aligned endpoints.

3.3. Operational framework for agronomic inference

3.3.1. Analytical validity: can the particle signal be trusted?

Analytical validity sets the first inferential boundary in MP/NP soil–plant research. It determines whether a reported signal can be used as evidence of occurrence, abundance, localization, transfer, or risk-related interpretation. Before any biological, ecological, or agronomic response is attributed to microplastic or nanoplastic exposure, the particle signal must be chemically identifiable, quantitatively bounded, and procedurally controlled. Visual recognition, fluorescence intensity, and particle-like morphology remain screening-level evidence unless polymer identity and matrix-specific controls are established. A suspected particle becomes an interpretable MP/NP signal only when polymer identification, particle-size resolution, recovery assessment, detection or quantification limits, procedural blanks, contamination control, and matrix-specific validation are reported [80,90,91].

Analytical approaches do not carry the same inferential weight. Visual inspection can isolate candidate particles, but it cannot reliably distinguish synthetic polymers from natural fibers, mineral fragments, biological debris, or organic residues. Comparative evidence from farmland soils shows that method selection controls detection accuracy, size range, and the type of evidence generated; visual, spectroscopic, imaging-based, and thermal workflows therefore support different levels of interpretation [80]. Fluorescence-based methods increase throughput but remain analytically limited when staining selectivity, segmentation criteria, false-positive control, blank correction, and reporting limits are not defined [91]. Spectroscopic methods strengthen polymer-confirmed occurrence and particle-level characterization, whereas thermal methods strengthen polymer-mass quantification. These outputs are not interchangeable. Particle-based evidence supports morphology and size distribution but not necessarily total polymer mass; mass-based evidence supports polymer load but not particle number, morphology, or localization.

Agricultural matrices intensify these constraints. Soil, compost, biosolids, manure, organic fertilizers, and plant tissues contain mineral particles, stable aggregates, altered organic matter, autofluorescent compounds, and fibrous biological material. These components generate false positives, obscure particles, and reduce extraction efficiency. In mass-based workflows, organic matter can overlap with polymer-derived thermal decomposition products and inflate polymer-mass estimates when matrix contributions are not corrected, particularly for polyethylene [90]. In particle-based workflows, soil aggregation and organic residues restrict extraction, recovery, and particle accessibility. Method-development evidence from agricultural soils and compost-amended systems confirms that extraction efficiency and particle accessibility depend on soil texture, organic matter, and aggregate stability [25,92].

Recovery efficiency and detection limits separate occurrence from abundance. Polymer identification without recovery validation stops the inference at occurrence; it does not justify abundance comparisons across soils, amendments, treatments, or particle-size fractions. Recovery varies with texture, organic matter, polymer density, particle size, aging status, and extraction chemistry [25,93]. The constraint becomes sharper for nanoplastics (<1 μm) and submicrometric particles because conventional spectroscopic methods have limited resolution at this scale, whereas mass-based methods cannot provide particle-size distributions. Without matrix-specific recovery, blank correction, and detection-limit reporting, non-detection cannot be interpreted as absence, and differences among matrices remain analytically underconstrained [91].

The analytical burden increases when the claim shifts from environmental occurrence to plant-tissue interpretation. Root-associated particles do not establish internalization, and tissue-associated signals do not establish translocation. Internalization requires evidence that separates external adhesion from internal localization through washing or desorption procedures, cross-sectional imaging, tracer-based mass balance, or high-resolution localization. Crack-entry pathways indicate that small plastic particles may enter crop roots through structural discontinuities associated with lateral root emergence under controlled conditions, but this mechanism cannot be generalized across polymers, crops, soils, or organs without particle-specific localization and exposure validation [77]. Soil-based biotests using traceable nanoplastics strengthen phytoavailability and compartment-level mass-balance assessment, but they do not establish edible-organ accumulation or food-safety relevance by themselves [56]. Root contact, internal localization, edible-organ accumulation, and food-safety relevance therefore require separate analytical thresholds.

Table 3 converts this boundary into claim-level thresholds. It separates occurrence, abundance, internalization, edible-organ accumulation, and food-safety relevance according to the analytical burden required for each claim. Polymer confirmation without recovery validation supports occurrence but not abundance. Recovery validation without polymer confirmation supports extraction performance but not particle identity. Root-associated detection without localization supports association but not internalization. Edible-compartment detection without bioaccessibility, dietary exposure, toxicity, or risk characterization does not support food-safety inference. This rule links Table 3 directly to Fig. 4: failure at the analytical layer prevents escalation, regardless of the strength of the downstream biological response. It also explains the lower tiers of Fig. 5, where particle detection and validated signal precede stronger biological, agronomic, or risk-oriented claims.

Once the particle signal has been analytically bounded, the next inferential question is not whether MPs/NPs can produce effects under controlled conditions, but whether the exposure scenario represents an agricultural soil–plant system.

3.3.2. Exposure realism: does the system approximate agricultural conditions?

Exposure realism sets the second inferential boundary in MP/NP soil–plant research. Once the particle signal is analytically defensible, the exposure scenario determines whether the evidence remains mechanistic or can enter an agronomic claim space. A validated MP/NP signal

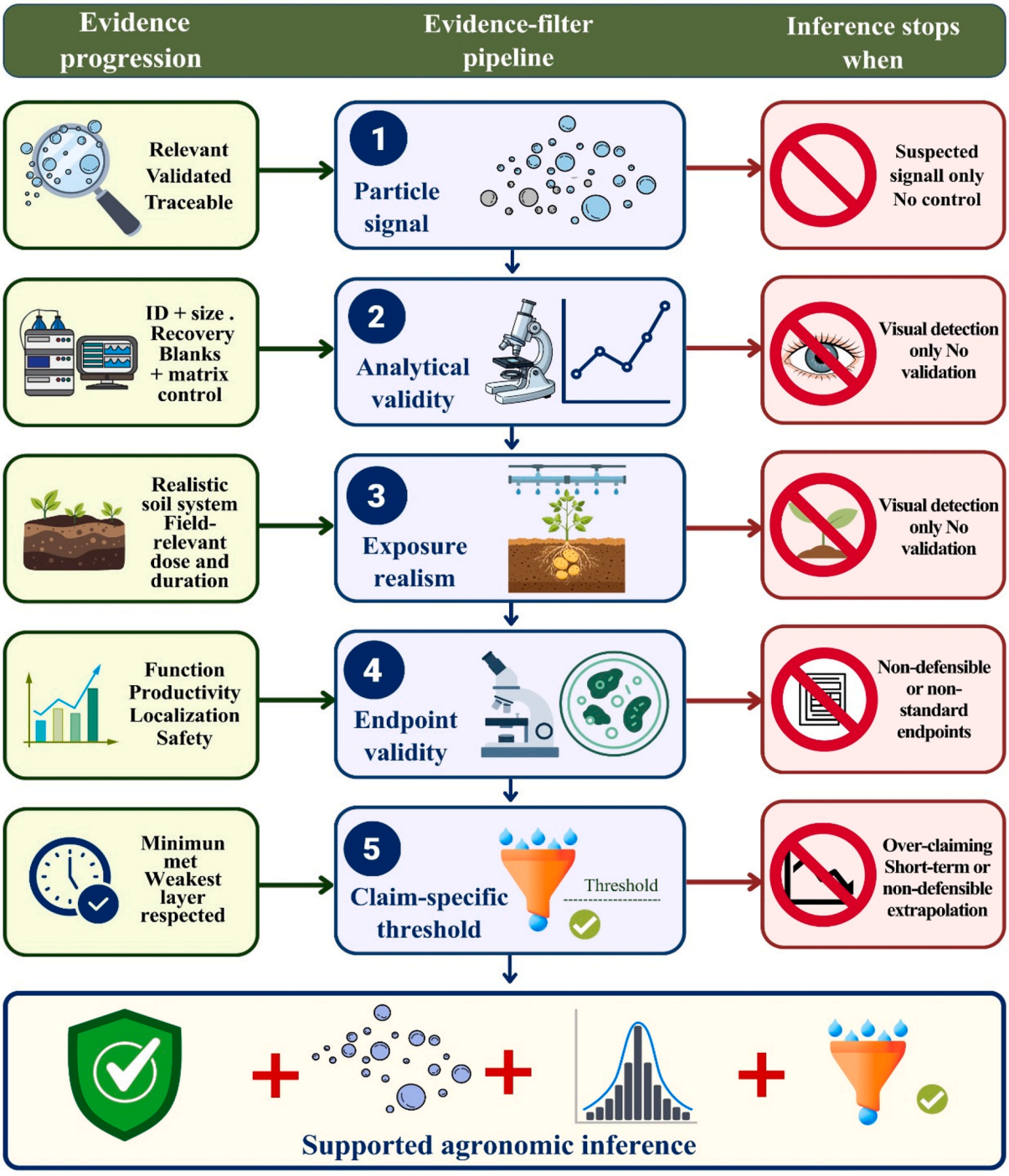

Fig. 4. Operational framework for agronomic inference in MP/NP soil–plant studies.
The framework represents agronomic inference as a sequential evidence-filter process with five filters: (1) particle signal, (2) analytical validity, (3) exposure realism, (4) endpoint validity, and (5) claim-specific threshold. Lateral panels indicate conditions that stop inference, including unconfirmed polymer identity, unrealistic exposure extrapolation, endpoint–claim mismatch, and unsupported escalation of short-term or mechanistic responses into agronomic claims. The framework follows a weakest-link rule: the least-supported evidence layer constrains the maximum defensible agronomic inference.

does not justify agricultural relevance when exposure occurs in simplified media, uses non-comparable dose metrics, relies on pristine particles detached from agricultural input pathways, or omits the soil processes that regulate particle mobility and bioavailability. Exposure realism therefore defines the agricultural scope of the claim by aligning six elements: matrix, input pathway, dose metric, exposure duration, particle condition, and management context.

The soil matrix is the first constraint. Hydroponic and nutrient-solution systems can isolate particle–root contact, early toxicity, or uptake mechanisms, but they remove the sorption, aggregation, pore architecture, organic matter interactions, mineral surfaces, microbial mediation, root exudation, hydrological flow, and aging processes that regulate MP/NP behavior in agricultural soils. Hydroponic evidence therefore remains bounded to root-level mechanisms unless it is followed by soil-based validation. Soil-based biotests, intact soil cores, rhizotrons, and lysimeter systems narrow this gap by reintroducing matrix constraints that liquid systems exclude [16,56,57]. Their inferential scope, however, remains controlled: they support soil–plant or

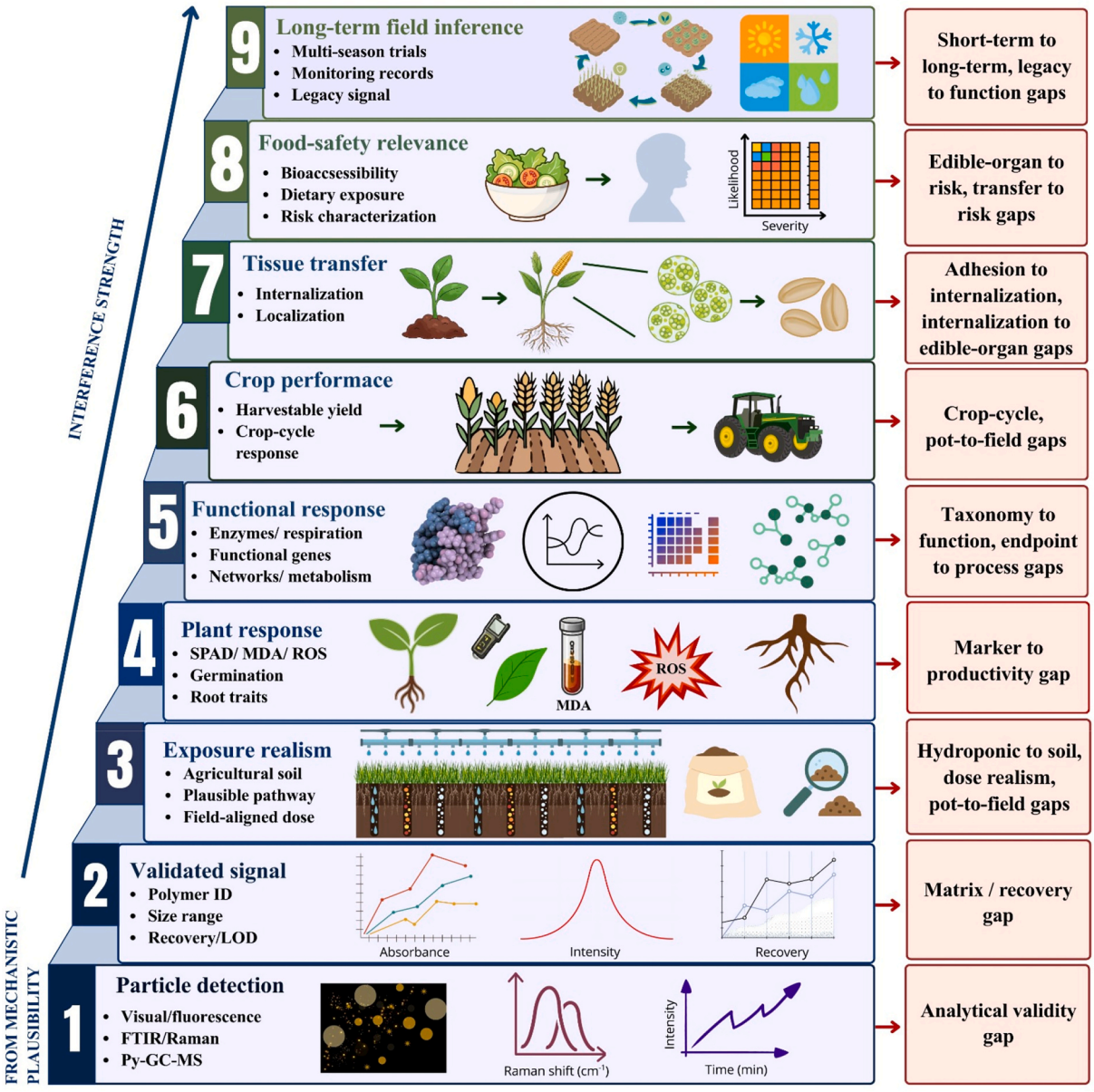

Fig. 5. Evidence hierarchy and translational bottlenecks limiting agronomic inference in MP/NP soil–plant studies.
The hierarchy presents nine levels of evidence escalation from mechanistic plausibility to supported agronomic inference. The vertical axis denotes increasing inferential strength; lateral red tags identify the main bottlenecks restricting claim escalation. Levels 1–3 establish the analytical and exposure foundation, with constraints including analytical-validity, matrix/recovery, hydroponic-to-soil, dose-realism, and pot-to-field gaps. Levels 4–6 represent biological-to-crop escalation, distinguishing marker-level responses from productivity claims and taxonomic shifts from functional disruption. Levels 7–9 define the strongest claim space; escalation depends on validated localization, edible-organ evidence, exposure or risk characterization, and temporally robust field support. The hierarchy separates mechanistic evidence from agronomic inference and shows that evidence escalates only when analytical validation, exposure realism, endpoint alignment, and temporal support increase together.

transport inference under defined conditions, not field-scale agronomic outcomes by themselves.

Exposure systems should be read by the maximum claim they can defend, not by a binary contrast between laboratory and field evidence. Hydroponic and in vitro assays support mechanistic inference. Soil microcosms support controlled soil responses. Pot studies with agricultural soil can support bounded soil–plant inference when dose, duration, and matrix are justified. Greenhouse and mesocosm systems increase agronomic plausibility when they include crop development and soil-based exposure. Field trials, monitoring datasets, archives, and legacy studies strengthen exposure realism because they incorporate management history, environmental variability, repeated inputs, and heterogeneous particle assemblages. Field evidence still does not remove the need for endpoint validity: monitoring or archive data can establish exposure relevance, but not functional loss, yield reduction, vector effects, or food-safety relevance unless the corresponding endpoints are measured. This distinction is necessary for interpreting pot crop-cycle studies, projected-dose greenhouse studies, field-plot transport experiments, and long-term monitoring records as different inferential classes rather than interchangeable evidence [16,35,53,59,60,94].

Dose realism depends on comparability, not only concentration. Experimental exposures reported as % w/w, mg kg^{-1}, particles kg^{-1}, items kg^{-1}, particles m^{-2}, or mg L^{-1} do not carry the same agronomic interpretability. High-dose % w/w designs can define stress-test conditions or mechanistic limits, but they do not support direct field-risk claims without calibration against agricultural burdens. A recurring

tension in the literature is the quantitative gap between experimental doses and environmental inventories. Reported agricultural soil concentrations typically range from hundreds to a few thousand particles kg^{-1} [5,12]. In contrast, mg kg^{-1}-based doses in controlled studies—including some framed as environmentally relevant—can correspond to particle numbers several orders of magnitude higher once converted, depending on particle size and polymer density. For example, 100 mg kg^{-1} in a soil with a given particle size distribution may represent 10^3 to 10^5 times the particle count of typical field burdens. This does not mean such studies lack value; it means their primary inferential contribution is mechanistic—identifying response thresholds, sensitive endpoints, and potential hazard—rather than directly projecting field-scale outcomes. The "one order of magnitude" criterion used in this framework for field-aligned exposure should therefore be understood as a screening threshold for mass-based doses, not as a universal equivalence across metrics or as a claim of environmental representativeness. Explicit particle-based conversion, where feasible, provides a more rigorous basis for dose comparability. Field monitoring and archive studies provide reference points for exposure ranges arising from biosolids, compost, plastic mulch, fertilizers, manure, wastewater irrigation, rainfall redistribution, and legacy contamination [39,60,92,95]. Projected or field-aligned mg kg^{-1} exposures can strengthen controlled soil–plant inference, but they still remain separated from field-scale claims when the system is confined to pots or short greenhouse assays [52]. Designs using elevated % w/w additions should therefore be treated as controlled exposure tests unless their dose, unit, and pathway are explicitly anchored to field burdens.

Particle condition and input pathway further delimit exposure realism. Agricultural soils rarely receive a uniform pulse of a single pristine polymer. They accumulate aged, fragmented, weathered, and mixed particles through mulch degradation, biodegradable mulch residues, biosolids, compost, manure or digestate, fertilizers, wastewater or reclaimed-water irrigation, tillage redistribution, rainfall-driven transport, and historical inputs. These pathways produce particles that differ from pristine laboratory materials in surface chemistry, density, fragmentation, sorption behavior, and interaction with soil biota. Field evidence from sweet potato soils documents mixed polymer assemblages rather than single-polymer exposure [54]. Compost-, biosolid-, fertilizer-, and manure-linked studies connect MP/NP presence to realistic agricultural entry routes [39,60,92]. Field designs incorporating mulch residues or simulated legacy loads increase pathway realism, but simulated loads and accelerated aging cannot substitute for decades of in situ transformation unless temporal processes are directly represented [43,96].

Duration defines the temporal reach of the claim. Acute or short-term exposures can support early response, transport, or mechanism-level inference. Crop-cycle studies provide stronger agronomic relevance because exposure interacts with phenology, biomass accumulation, and harvestable endpoints. Multi-season, monitoring, archive, and legacy studies provide stronger temporal realism because they capture repeated inputs, weathering, redistribution, and accumulation across management histories. Evidence from long-term sludge-amended fields and agricultural topsoil archives supports legacy exposure relevance and field accumulation patterns [35,59,60]. These studies set the exposure context for long-term inference, but they do not establish productivity decline, microbial functional impairment, contaminant transfer, or food-safety relevance without endpoint evidence aligned with those claims.

The exposure-realism filter in Fig. 4 prevents a validated particle signal from being escalated when the exposure system lacks soil relevance, plausible input pathways, comparable dose metrics, crop-relevant duration, or field-relevant particle condition. In Fig. 5, exposure realism occupies the transition between validated detection and higher-level evidence; without it, biological responses remain mechanistic rather than agronomically interpretable. Table 3 applies this constraint at the claim level: soil degradation, crop performance, contaminant-vector effects, field relevance, long-term inference, and food-safety relevance require exposure conditions that match the matrix, pathway, dose, duration, and particle condition of the claim. Once exposure realism is established, claim escalation depends on endpoint validity: the measured response must correspond to the process, outcome, or risk being asserted.

3.3.3. *Endpoint validity: does the measured response support the claim?*

Endpoint validity sets the third inferential boundary in MP/NP soil–plant research: analytically validated particles and agriculturally realistic exposure cannot support a claim unless the measured response corresponds to the process, outcome, transfer pathway, or risk being asserted. The central question is not whether a response changed after MP/NP exposure, but whether the endpoint is the right evidence for the claim. Proxy endpoints can support restricted interpretations, but they cannot be escalated into outcome-level claims without additional evidence. Multiple proxy endpoints also do not create a stronger claim. Physiological stress, early growth, taxonomic restructuring, contaminant association, and particle adhesion each remain bounded by their own inferential level.

This boundary is clearest for plant-response endpoints. SPAD, chlorophyll, antioxidant activity, MDA, ROS, proline, ion fluxes, and related biochemical markers support plant physiological-stress inference, but they do not establish crop-performance loss. Germination, root length, seedling biomass, and early vegetative traits support establishment or early-growth responses, not full crop-cycle productivity. Controlled studies using physiological or early-growth endpoints therefore remain bounded to plant-response inference unless mature biomass, harvestable yield, or crop-cycle performance is measured [46,52]. Evidence combining physiological traits with fruit-quality and yield-related variables reinforces this boundary because changes in stress or quality markers do not necessarily translate into significant changes in fruit number or fruit weight [53]. The claim cannot move from plant response to crop performance unless the endpoint measures crop performance.

The same restriction applies to microbial endpoints. Taxonomic restructuring supports community-response inference but does not establish microbial functional response or impairment without process-oriented evidence. Diversity indices (Shannon, Chao1), amplicon sequence variants (ASVs), operational taxonomic units (OTUs), PCoA separation, community composition, and co-occurrence patterns document community restructuring but do not measure microbial process rates [97–100]. Functional claims require activity-linked endpoints such as enzyme activity, respiration, heat-flow dynamics, nutrient-cycling rates, or flux measurements [101,102]. Functional genes, KEGG pathways, and metabolomic profiles indicate functional potential or pathway-level response, but they do not substitute for measured activity or process-rate endpoints. Even omics-based data require bounded interpretation. Process-oriented endpoints such as microcalorimetry and metabolic heat-flow provide stronger evidence of microbial activity, but their agronomic interpretation still requires linkage to soil processes, crop response, or field-scale function [29,51,103].

Soil physical and biogeochemical endpoints require the same endpoint-to-claim discipline. Soil physical variables such as bulk density, porosity, water retention, and aggregate stability support structural or hydraulic claims when they measure the asserted process. Biogeochemical variables such as pH, electrical conductivity, mineral nitrogen, DOC, nutrient pools, or metal lability support nutrient- or contaminant-process claims only when linked to fluxes, availability, uptake, or functional consequences [104,105]. A change in soil physical structure does not establish crop-performance loss by itself, and a change in nutrient availability does not establish yield decline. Soil-state endpoints under pot conditions support soil alteration, but field degradation or crop-performance claims require linkage to plant performance, hydraulic function, or field-scale behavior [106]. High-resolution assessment of nutrient availability at the soil–water interface strengthens biogeochemical interpretation, but it cannot be treated as rice yield or

agronomic loss without harvest or process-scale endpoints [49]. Shifts in carbon formation pathways support carbon-process interpretation, but short-term or two-year responses should not be escalated into permanent SOC sequestration without longer-term stock measurements [48].

Transfer-related claims require connected evidence across compartments. Sorption alone does not establish a contaminant-vector effect, and mobility alone does not establish biological transfer. Consistent with the evidentiary standard established above, a vector-effect claim is defensible only when the same experimental system provides linked evidence of polymer–contaminant interaction, contaminant mobility or bioavailability, and subsequent biological uptake or transfer. Sorption-only endpoints, by contrast, remain interaction-level evidence and do not justify vector-effect attribution. Evidence linking sulfamethoxazole bioavailability or plant-tissue transfer in a pot system provides stronger transfer-oriented support than sorption-only endpoints, but it remains bounded by the experimental system in which the transfer was measured [33]. Field co-occurrence between MPs and cadmium supports contaminant-association evidence, not MP-driven metal uptake, because correlation in field soil does not establish a transfer pathway [54]. Evidence for bacterial pathogen survival and transfer on plastic-associated particles supports biological-vector plausibility, but human infection risk requires exposure assessment or dose–response characterization [55]. Without same-system evidence, contaminant interaction remains association rather than vector-effect evidence.

Internalization, edible-organ accumulation, food-safety relevance, and long-term field inference impose higher endpoint thresholds. Root-associated particles do not establish internalization, and root-mediated movement does not prove systemic transport [57,77,107]. Evidence that separates root-associated movement or mucilage adhesion from vascular localization is therefore more informative than surface detection alone [57].

Validated tissue localization can support internalization or tissue-level occurrence, but the evidentiary threshold depends on the analytical method's capacity to distinguish internalized particles from surface-associated residues, mucilage entrapment, or procedural artifacts. Confocal laser scanning microscopy (CLSM) with fluorescent labeling can visualize particles within tissue sections, yet it is susceptible to false positives from dye leakage, photobleaching, and biological autofluorescence, requiring rigorous procedural controls [108]. Surface-enhanced Raman spectroscopy (SERS) offers higher chemical specificity and enables in-situ localization with sub-micrometre resolution, though its application to plant tissues remains technically demanding [109]. Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) provides unambiguous polymer identification and quantification in bulk tissue extracts, but it does not provide spatial localization; detection by Py-GC/MS in bulk tissue confirms polymer presence but does not, by itself, establish internalization unless preceded by rigorous surface-interior separation protocols [108]. For internalization claims, the minimum standard is CLSM with appropriate controls or SERS imaging demonstrating particle presence within the tissue interior, beyond the root epidermis or apoplastic space. However, internalization does not establish edible-organ accumulation unless the edible compartment is analyzed with adequate localization or extraction control [77]. Validated detection in edible organs can support edible-compartment occurrence, but food-safety relevance requires bioaccessibility, dietary exposure, toxicity, or risk characterization [32]. Long-term exposure or legacy presence also does not establish long-term agronomic impact unless functional or crop-level endpoints are measured. Persistence and fragmentation decades after sludge application support long-term exposure relevance, not current microbial toxicity or productivity loss without concurrent endpoint evidence [35]. Evidence separating short-term crop response from fungal-network stability further indicates that crop performance and long-term soil resilience require different endpoints [110].

Endpoint validity therefore closes the third filter of the inference framework. A measured response can support a claim only when it matches the inferential level of that claim: marker-level endpoints remain marker-level evidence, taxonomic endpoints remain community-structure evidence, sorption or association endpoints remain interaction evidence, and short-term endpoints remain temporally bounded evidence.

3.3.4. *Claim-specific thresholds for agronomic inference*

Claim-specific thresholds translate analytical validity, exposure realism, and endpoint validity into the minimum evidentiary configuration required for each inference. A claim is defensible only at the highest level jointly supported by all three filters; strength in one evidentiary layer cannot compensate for failure in another. Robust polymer identification does not rescue an unrealistic exposure scenario, field exposure does not rescue a weak endpoint, and multiple proxy responses do not amount to an outcome-level measurement. Table 3 should therefore be read as a decision matrix rather than as a catalogue of effects: it defines the minimum analytical, exposure, and endpoint conditions required before each claim category can be defended.

At the lower end of the hierarchy, occurrence and abundance claims are primarily constrained by analytical thresholds. Polymer-confirmed occurrence supports presence in a defined matrix, but it does not establish abundance, biological effect, or agronomic relevance. Abundance or polymer-load claims require additional evidence: recovery assessment with matrix-specific correction, procedural blanks for contamination control, detection and quantification limits (LOD/LOQ), particle-size resolution, and comparable units that enable cross-study or cross-matrix comparisons.

Metric incompatibility is a recurrent barrier. Count-based (particles kg^{-1}, items kg^{-1}, particles m^{-2}), mass-based (mg kg^{-1}, % w/w), and concentration-based (mg L^{-1}) units are not directly interchangeable; meaningful conversion requires particle density, size distribution, polymer-specific mass, and matrix-specific recovery factors—parameters rarely reported together. Method-dependent recovery, fluorescence limitations, blank contamination, and polymer-mass overestimation (e.g., via pyrolysis-GC/MS) further constrain the reliability of abundance estimates [80,90,91]. Without these analytical controls, the particle signal remains insufficient for robust abundance contrasts, defensible field-burden estimates, or attribution of biological or risk-related effects to MP/NP exposure.

For soil and microbial claims, the threshold shifts from state description to process measurement. Soil physical degradation requires structural or hydraulic endpoints, such as bulk density, porosity, aggregation, water retention, infiltration, or hydraulic conductivity, measured under exposure scenarios relevant to soil function. Soil biogeochemical disruption requires process-linked evidence, including mineralization, enzyme activity, gas fluxes, carbon-pool dynamics, contaminant availability linked to mobility or uptake, or nutrient availability interpreted in relation to functional consequences [26,47,61]. Microbial functional-response claims likewise cannot be inferred from community restructuring alone. Community composition, diversity indices, ASVs, OTUs, PCoA separation, and co-occurrence networks support community-structure claims, but function requires activity-oriented evidence such as enzyme activity, respiration, microcalorimetry, nutrient fluxes, metabolic activity, or measured process rates. Functional genes and KEGG pathways primarily support functional potential, whereas respiration, microcalorimetry, metabolic activity, and flux-oriented endpoints provide stronger evidence of realized microbial function when linked to process interpretation [29,111].

Plant-response and crop-performance claims require a separate threshold. Physiological stress, photosynthetic markers, oxidative-stress responses, early growth, and root traits can support plant-response inference, but they do not establish crop-performance loss. Crop-performance claims require endpoints measured at the appropriate developmental or harvest scale, including mature biomass, fruit number, fruit weight, grain yield, tuber yield, harvestable biomass, commercial quality when the claim concerns marketable performance, or

Table 4
Research priorities and design transitions required to close translational bottlenecks in MP/NP soil–plant research.

Translational bottleneck	Current design limitation	Required design transition	Minimum measurements	Required configuration	Inference strengthened	Inference still unsupported	Priority	Representative evidence basis
Analytical comparability and matrix-recovery gap	Particle counts, polymer mass, fluorescence signals, and visual detections are reported with inconsistent recovery, blank correction, matrix control, and size limits.	Replace method-specific detection with matrix-validated reporting of particle occurrence, abundance, and polymer load.	Polymer ID; size distribution; morphology; blanks; recovery; LOD/LOQ; matrix interference; particle and/or mass units.	Soil, compost, biosolid, fertilizer, plant tissue, or edible-organ matrices with matrix-specific validation; occurrence, abundance, localization, or edible-organ burden matched to analytical capability.	Comparable occurrence, abundance, and localization claims.	Biological effect, internalization, field burden, or food-safety relevance remains unsupported without exposure and endpoint evidence.	High	[80,90,91]
Field-calibrated exposure and pot-to-field gap	Controlled systems often use arbitrary doses, confined rooting volume, simplified hydrology, or non-comparable units detached from agricultural input rates.	Replace arbitrary/elevated dosing and confined systems with field-calibrated exposure gradients and field-structured soil designs.	MP/NP burden by mass and/or particle number; particle-size distribution; dose–response curves; soil-profile burden; runoff or infiltration metrics.	Agricultural soil; comparable units; defined input pathway; loading pattern linked to mulch, biosolids, compost, fertilizer, irrigation, or legacy inputs; crop-cycle, soil-process, transport, or transfer endpoint aligned with the exposure claim.	Field-aligned exposure and soil-profile mobility inference under defined soil–crop conditions.	Chronic field impact, food-safety relevance, or landscape-scale transport remains unsupported without multi-season endpoints and broader exposure assessment.	High	[16,57,94]
Temporal validation and legacy-to-current-impact gap	Acute, single-season, archive, or monitoring studies document response, persistence, or accumulation without linking exposure history to concurrent functional outcomes.	Replace short-term or legacy-only evidence with multi-season or paired legacy-impact designs using repeated measurements and concurrent endpoints.	MP/NP burden over time; aging; fragmentation; spatial distribution; soil function; microbial activity; crop performance; post-exposure recovery.	Repeated or legacy input scenario; documented management history; paired controls; multi-season field or semi-field exposure; long-term functional, crop-performance, transfer, or risk-relevant endpoint measured across seasons or in paired legacy systems.	Long-term field inference linking exposure history with present-day system response.	Permanent SOC change, decadal resilience, productivity loss, or food-safety relevance remains unsupported without longer time series and endpoint-specific evidence.	High	[35,48,59,110]
Fragmented-endpoint-to-integrated-system gap	Particles, soil properties, microbiome, plant response, contaminant transfer, and productivity are often measured in separate designs.	Replace disconnected endpoints with same-system soil–microbiome–plant designs using concurrent particle, process, plant, and transfer measurements.	Particle burden; soil physical/chemical variables; microbial function; nutrient or contaminant process; plant physiology; crop performance; tissue or transfer endpoint when relevant.	Agricultural soil; plausible input pathway; justified dose; defined particle condition; crop-cycle duration; linked endpoints measured in the same experimental units, pots, lysimeters, or field plots.	Mechanistic chains linking MP/NP exposure to soil processes, microbial function, plant response, and crop performance.	Causal field-level impact remains unsupported without replication, temporal validation, and confounder control.	High	[29,52,53,101]
Taxonomy-to-function gap	Microbial diversity, 16S/ITS profiles, ASVs, OTUs, and co-occurrence networks are often interpreted as functional disruption.	Replace taxonomic profiling alone with process-linked microbial function measured in the same soil–plant system.	Enzyme activity; respiration; microcalorimetry; nutrient mineralization; N, C, or P fluxes; functional genes interpreted with process endpoints.	Rhizosphere or agricultural soil; realistic amendment or fertilization context; exposure duration aligned with microbial process response; process-rate endpoint linked to microbial activity, nutrient cycling, or soil function.	Microbial functional response and process-level soil interpretation.	Soil health degradation, crop-performance loss, or ecosystem-service decline remains unsupported without functional persistence and crop or field-scale linkage.	High	[29,51,101,103]
Marker-to-productivity gap	Physiological, biochemical, or early-growth markers are used as proxies for crop productivity without harvest-scale validation.	Replace marker-level response with crop-cycle performance assessment within the same experimental units.	Physiological markers where relevant; mature biomass; harvestable yield; fruit/grain/tuber number and weight; marketable quality when claimed.	Soil-based exposure; completed crop cycle; justified dose and pathway; crop species and developmental stage defined; harvestable yield, mature biomass, marketable quality, or crop-cycle performance endpoint.	Crop-performance inference under defined exposure conditions.	Field-scale yield loss, economic impact, or food-safety relevance remains unsupported without field validation and edible-organ or risk-oriented evidence.	High	[46,53,94]
Sorption-to-vector gap	Sorption, desorption, mobility, or field co-occurrence is treated as evidence that MP/NPs	Replace sorption-only evidence with same-system contaminant mobility, bioavailability, and biological uptake or transfer.	Contaminant concentration in soil solution and tissues; polymer-associated contaminant load; mobility	Soil-based co-exposure; contaminant and polymer linked to plausible agricultural pathways; moisture regime defined; same-system transfer endpoint linking	Contaminant-vector effect under defined exposure conditions.	Food-chain relevance or formal human-health risk remains unsupported without dietary exposure,	Medium	[33,54,55]

(*continued on next page*)

Table 4 (*continued*)

Translational bottleneck	Current design limitation	Required design transition	Minimum measurements	Required configuration	Inference strengthened	Inference still unsupported	Priority	Representative evidence basis
	act as contaminant vectors.		metrics; uptake or translocation factors.	particle–contaminant interaction to plant uptake or biological transfer.		toxicity, and broader validation.		
Root-association-to-internalization gap	Root-surface particles, fluorescence signals, or tissue-associated detections are treated as internalization or systemic translocation.	Replace surface association with validated localization or extraction-controlled evidence separating adhesion, entrapment, internalization, and translocation.	Washing/desorption controls; cross-sectional imaging; tracer-based mass balance; validated spectroscopy or microscopy; compartment-specific particle burden.	Soil–plant system; particle size and chemistry defined; submicrometric or nanoplastic fractions characterized when internalization is claimed; validated tissue-localization, extraction-controlled internalization, or vascular/translocation endpoint.	Tissue-level internalization or translocation under validated analytical conditions.	Whole-plant toxicity, edible-organ accumulation, or food-safety relevance remains unsupported unless edible compartments and exposure-oriented endpoints are analyzed.	Medium	[36,56,57,114]
Edible-organ-to-food-safety gap	Detection in roots, leaves, or edible tissues is used to imply food-safety relevance without exposure, bioaccessibility, or toxicity assessment.	Replace edible-organ detection with exposure-oriented food-safety assessment.	Particle burden in edible compartment; surface/interior distinction; bioaccessibility; dietary exposure metrics; contaminant or additive co-exposure where relevant.	Crop consumed by humans or animals; realistic soil exposure; harvest-stage sampling; contamination controls during tissue processing; edible-organ endpoint linked to bioaccessibility, dietary exposure, hazard context, or risk characterization.	Food-safety relevance under defined crop–exposure scenarios.	Formal human-health risk assessment remains unsupported without toxicity, dose–response, dietary intake, and risk characterization.	Medium	[32,58,114]
Pristine-single-polymer-to-aged-mixture gap	Laboratory studies frequently use pristine single polymers that do not represent aged, fragmented, additive-bearing, or mixed agricultural residues.	Replace pristine single-polymer assays with representative aged mixtures and controlled factorial mixture designs based on plausible agricultural inputs.	Polymer mixture profile; aging indicators; particle-size distribution; surface chemistry; additive or co-contaminant load; biofilm or mineral coating where relevant.	Weathered mulch fragments, compost/biosolid-derived particles, wastewater-associated particles, or field-aged residues; mixture composition justified by input pathway; endpoint matched to material complexity.	Material-realism inference for agricultural MP/NP exposure.	Generalizable toxicity, long-term risk, or additive-specific effects remain unsupported without controlled mixture composition and mechanistic attribution.	High	[35,59,96,110]

Note. Table 4 is a design-transition matrix, not an evidence-summary table. "Representative evidence basis" lists selected sources supporting the limitation or transition; it is not an exhaustive citation list. Priority reflects the strategic value and feasibility of each transition for strengthening agronomic inference, not the presumed severity of MP/NP effects. "Inference strengthened" identifies the interpretation made more defensible by the proposed design transition; "Inference still unsupported" identifies the higher-level claim that remains blocked unless additional analytical, exposure, endpoint, temporal, or risk-oriented evidence is added.

crop-cycle performance. Controlled evidence can support plant response or bounded crop-cycle inference, but it cannot be escalated to field-scale yield loss without exposure realism, endpoint alignment, and, where needed, field validation [94]. Physiological or quality-related changes without corresponding changes in yield components exemplify the marker-to-productivity gap [53].

Transfer, internalization, edible-organ accumulation, and food-safety relevance claims impose higher evidentiary burdens because they require connected evidence across compartments. Vector-effect attribution, under the framework applied throughout this review, demands more than interaction or mobility evidence. It requires that polymer presence, contaminant partitioning or bioavailability, and organismal uptake or transfer be measured within the same experimental system, a standard that sorption-only or co-occurrence data cannot satisfy [65,112,113]. Sorption alone is not vector effect; field co-occurrence is not transfer; correlation between MPs and contaminants in soil does not establish MP-driven uptake [33,54]. Biological-vector plausibility, including pathogen survival or transfer on plastic-associated particles, does not establish human infection risk without exposure assessment or dose–response characterization [55]. Particle-internalization claims impose a separate localization threshold. They require validated tissue-localization or extraction-controlled evidence that distinguishes internal particles from surface adhesion, mucilage entrapment, or matrix contamination. Root-associated movement or adhesion does not establish internalization, whereas validated tissue-localization or extraction-controlled evidence can support internalization or tissue-level occurrence [57,114]. Internalization does not establish edible-organ accumulation unless the edible compartment is directly analyzed. Food-safety relevance requires an additional threshold: edible-organ evidence must be linked to bioaccessibility, dietary exposure, toxicity, hazard characterization, or risk assessment. Detection in plant tissue or edible organs is therefore not equivalent to food-safety relevance or human-health risk [32].

Long-term field inference occupies the upper end of the threshold hierarchy because it requires temporal alignment between exposure history and the endpoint being asserted. Archive and monitoring studies can support long-term exposure relevance, persistence, weathering, dispersal, or historical accumulation, but not current functional impairment or crop-performance loss by themselves [35,60]. Multi-year field trials with concurrent endpoint measurement provide stronger temporally bounded evidence of functional change, although intermediate-duration responses remain limited by the duration and endpoint structure of the study. Two-year carbon-process shifts can support biogeochemical interpretation, but not permanent SOC sequestration or multidecadal soil-function claims without longer stock-based evidence [48]. Short-term crop responses and microbial-network stability also require different endpoints and should not be collapsed into a single impact claim [110]. Long-term exposure relevance is not long-term field impact unless functional, crop-level, transfer, or risk endpoints are measured at the appropriate temporal scale.

The threshold framework blocks upward claim escalation by assigning each inference to the lowest evidentiary layer that is jointly supported by analytical validity, exposure realism, and endpoint validity. Evidence may support occurrence, stress, association, exposure, transfer plausibility, or persistence without supporting crop-performance loss, contaminant-vector effect, food-safety relevance, or long-term field inference. In this sense, Figs. 4 and 5 do not merely organize the evidence; they delimit where the inference must stop when any required layer fails.

3.4. Research roadmap for closing translational bottlenecks

The operational framework developed in Section 3.3 defines the evidentiary conditions under which MP/NP observations can support agronomic inference. The remaining challenge is to translate those inferential boundaries into research designs capable of closing the main translational bottlenecks. Table 4 converts these bottlenecks into design transitions, while Fig. 6 summarizes the same logic as a roadmap organized around five research priorities and a cross-cutting analytical foundation. This foundation refers to polymer identification, recovery assessment, blanks, detection limits, matrix controls, and size-resolved reporting as prerequisites for all roadmap transitions. The following subsections do not repeat the evidence hierarchy; they define how future studies should be redesigned to generate claim-aligned agronomic inference.

3.4.1. Long-term validation and legacy-to-current-impact linkage

Temporal validation should not be reduced to study duration; it requires designs that connect exposure history with present-day functional outcomes. Acute assays, single-season field studies, archive records, and monitoring datasets can document particle occurrence, persistence, redistribution, or accumulation, but they cannot support long-term agronomic claims when they remain disconnected from current soil, microbial, crop, transfer, or recovery endpoints. Long-term monitoring and legacy evidence are valuable because they establish whether plastic particles persist, fragment, and redistribute under agricultural management [35,59]. However, persistence and accumulation remain exposure-level evidence until they are paired with concurrent functional, agronomic, transfer, or recovery endpoints.

Closing this bottleneck requires replacing short-term or legacy-only evidence with multi-season and legacy-paired designs. These designs must measure MP/NP burden repeatedly and combine it with particle aging, fragmentation, spatial distribution, and concurrent functional or crop-relevant endpoints. Duration alone is insufficient. The design must include repeated or legacy input scenarios, documented management history, paired controls, and multi-season field or semi-field exposure to separate MP/NP-associated responses from broader historical management effects. Without this structure, archive and monitoring datasets can reconstruct exposure histories, but they cannot support attribution of present-day soil or crop responses to MP/NP legacy.

The current evidence base supports this design transition rather than the higher-level claims themselves. When repeated exposure and concurrent endpoints are measured in the same system, multi-season evidence can strengthen the link between polymer exposure history and selected biogeochemical responses, including carbon-cycling pathways [48]. By contrast, legacy or archive evidence spanning several decades can support persistence, fragmentation, and historical accumulation inference, but it remains insufficient for claims about contemporary microbial functional impairment, productivity loss, or food-safety relevance when concurrent endpoints are absent [35,59]. Long-term soil organic carbon (SOC) stock change, long-term soil resilience, productivity loss, and food-safety relevance require longer or repeated temporal records combined with endpoint-specific functional, agronomic, or risk-oriented measurements.

This transition defines the first design priority of the roadmap: exposure history must be linked to present-day endpoints before long-term agronomic inference can be strengthened. Multi-season and legacy-paired designs strengthen long-term field inference, but they do not replace claim-aligned endpoints or realistic exposure systems. Temporal validation therefore becomes agronomically informative only when exposure history, field-calibrated conditions, and claim-aligned endpoints are combined within the same design. This leads directly to the next roadmap priority: realistic exposure systems and field calibration.

3.4.2. Realistic exposure systems: matrices, doses, pathways, and field calibration

Exposure design determines whether an MP/NP response can be interpreted as agriculturally meaningful. Realism should not be reduced to the phrase “environmentally relevant concentration”; it requires five linked descriptors: matrix, dose unit, input pathway, particle condition,

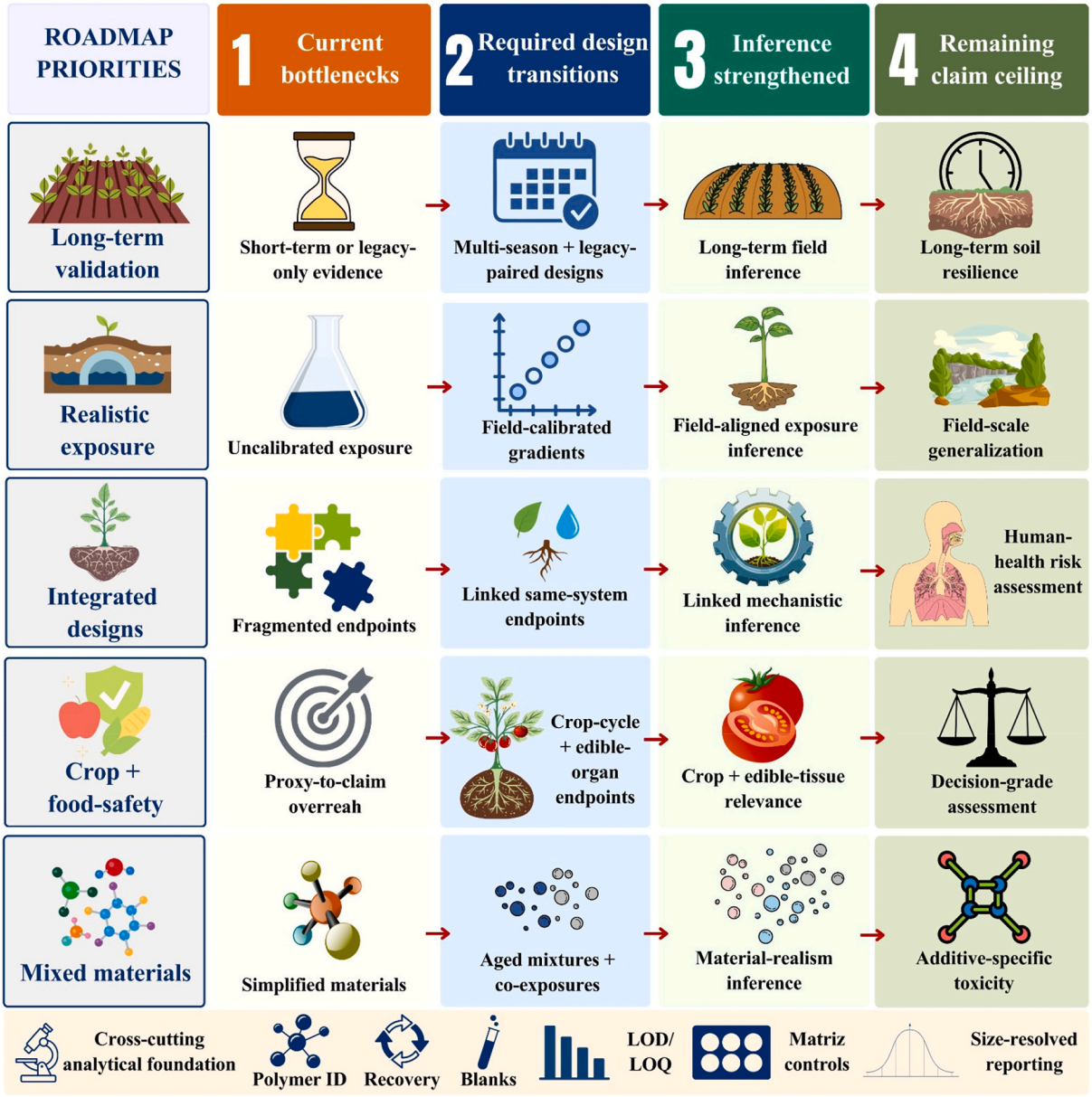

Fig. 6. Roadmap for closing translational bottlenecks in MP/NP soil–plant research.
The figure organizes five research priorities into a design-oriented roadmap linking current bottlenecks, required design transitions, strengthened inference, and remaining claim ceilings. Long-term validation requires moving from short-term or legacy-only evidence toward multi-season and legacy-paired designs. Realistic exposure systems require replacing uncalibrated exposure scenarios with field-calibrated gradients. Integrated designs require linking fragmented endpoints within the same soil–microbiome–plant experimental framework. Crop and food-safety relevance requires moving from proxy-based responses toward crop-cycle, edible-organ, and transfer-oriented endpoints. Material realism requires moving from simplified materials toward characterized aged mixtures and co-exposure systems while preserving attribution. The rightmost column identifies claims that remain beyond each design transition unless additional evidence is generated, and the bottom band defines the cross-cutting analytical foundation required across all priorities: polymer identification, recovery assessment, blanks, LOD/LOQ, matrix controls, and size-resolved reporting.

and exposure duration. Without these descriptors, biological responses remain tied to an experimental construct rather than to an agricultural exposure scenario. The required transition is therefore from uncalibrated spiking and simplified exposure systems toward field-calibrated gradients embedded in soil matrices and input pathways that match the claim being advanced.

Dose calibration sets the first boundary. Soil doses expressed as mg kg^{-1}, field burdens expressed as particles kg^{-1}, % w/w additions, and mg L^{-1} solution exposures do not describe equivalent exposure states unless they are translated into comparable soil burdens. Projected soil concentrations can align controlled experiments with present or plausible near-future accumulation scenarios, while monitoring and archive datasets anchor experimental loading to agricultural inputs such as biosolids, fertilizers, and manure [39,60,94]. High % w/w additions and mg L^{-1} solution exposures still have value, but mainly as mechanistic stress tests. They identify sensitivity or exposure–response patterns; they do not define field-aligned agronomic exposure unless the imposed loading is calibrated against measured or projected agricultural burdens.

Matrix and pathway calibration define the second boundary. Hydroponic, solution-based, gel-based media, or artificial-substrate systems isolate root-contact, uptake, or cellular mechanisms, but they remove the mineral, organic, structural, and hydrological controls that govern particle retention, transport, and bioavailability in soil. Soil-based biotests, amended agricultural soils, intact soil profiles,

lysimeters, and rhizotrons move the design closer to agricultural exposure by reintroducing matrix interactions, profile structure, or root-mediated transport [56,57,106]. These systems, however, do not occupy the same inferential level. A soil-based biotest reduces hydroponic-to-soil extrapolation; intact cores and lysimeters strengthen soil-profile mobility inference. Neither design, by itself, establishes field-scale impact.

Agricultural pathways must drive the exposure scenario. Direct spiking with pristine particles remains useful for isolating mechanisms, but it poorly represents field exposure when the claim concerns residues from mulch degradation, biosolids, compost, manure, fertilizers, irrigation water, rainfall redistribution, tillage, or legacy inputs. Particle condition also matters at this stage: aged, weathered, fragmented, or field-derived particles should enter the design when they modify retention, transport, or bioavailability under realistic soil pathways. This is not yet the broader material-realism problem of mixed polymers, additives, and co-contaminants; that issue is addressed later. Here, the narrower requirement is exposure fidelity: the design must represent how particles enter, persist, and move within agricultural soil before downstream endpoints can be interpreted agronomically.

Field calibration therefore limits the strongest claim that exposure evidence can support. Monitoring, archive, biosolid, compost, fertilizer, and legacy datasets calibrate exposure ranges and pathways; they do not attribute functional impairment, productivity loss, transfer, or risk outcomes without endpoint-specific measurements. Likewise, intact cores, lysimeters, and rhizotrons preserve structure, hydrological gradients, or root-mediated movement, but they remain controlled systems. The defensible claim from this roadmap priority is field-aligned exposure inference, not field-scale agronomic impact. Once exposure is calibrated, the next task is to link soil, microbiome, and plant measurements within the same experimental framework.

3.4.3. *Integrated soil–microbiome–plant designs and functional endpoint linkage*

Integrated design must move MP/NP soil–plant research from endpoint accumulation to pathway construction. After exposure has been field-calibrated, the central requirement is to connect particle burden, soil state, microbial activity, rhizosphere dynamics, and plant response within the same experimental units or plots. This connection requires matched exposure levels, synchronized sampling across relevant growth stages, and compartment-resolved measurements that allow the response sequence to be interpreted. A study becomes integrative not because it reports many variables, but because those variables form an interpretable chain linking particle exposure to soil processes, microbial function, and plant response.

This chain must treat microbial data according to their inferential level. Diversity metrics, amplicon profiles, ordination patterns, and co-occurrence networks characterize microbial restructuring; they provide the structural layer of the mechanism. Functional genes, KEGG profiles, metagenomic outputs, and predicted functions define functional potential. Realized function requires activity- or flux-linked evidence, including respiration, gas fluxes, nutrient transformation rates, microcalorimetric heat-flow dynamics, or enzyme activity interpreted within a temporal or process-based context. The strongest designs link these layers instead of treating one as a substitute for another: community structure should be connected to functional potential, functional potential to measured activity, and microbial activity to soil or plant outcomes [29,111].

Integrated soil–microbiome–plant studies should also be designed to distinguish among competing response pathways. A plant response under MP/NP exposure may arise from altered soil structure, nutrient availability, microbial functional shifts, direct particle–root contact, co-occurring contaminants, or their interaction. Same-system designs can address this complexity when they combine compartment-resolved sampling with factorial or mediation-oriented contrasts. Designs that connect rhizosphere functional genes, soil chemistry, microbial activity, plant metabolism, and biomass response within the same experimental structure provide stronger pathway-level inference than studies that assemble those signals across separate experiments or unrelated time points [48,73,103].

The value of integration lies in tracing response propagation across compartments. It allows researchers to ask where MP/NP-associated responses emerge, whether they pass through soil or microbial processes, and whether they reach plant-level outcomes. This type of evidence strengthens linked mechanistic inference, which is the appropriate claim for this roadmap priority. It does not need to be framed as proof of field-scale impact to be valuable; its role is to convert disconnected observations into a testable soil–microbiome–plant mechanism. The next design priority is to determine whether those mechanisms translate into harvestable yield, edible-tissue occurrence, contaminant transfer, or exposure-oriented food-safety relevance.

3.4.4. *Crop productivity, edible tissues, contaminant transfer, and food-safety relevance*

This priority addresses the transition from proxy-based responses to endpoints that can directly support bounded crop-performance, transfer, edible-compartment, or food-safety-relevance claims, corresponding to the marker-to-productivity, sorption-to-vector, and edible-organ-to-food-safety transitions in Table 4 and the fourth lane of Fig. 6. Crop-performance claims require harvest-scale endpoints, whereas food-safety-relevance claims require edible-compartment burden linked to exposure-oriented assessment. Physiological stress, early growth inhibition, sorption, field co-occurrence, root association, and tissue detection remain useful mechanistic signals, but they define only the starting point of inference. The required transition is from proxy responses to endpoints that capture productivity, edible-organ occurrence, biological transfer, and exposure relevance within the same crop, edible-compartment, or exposure-oriented context.

Productivity-oriented studies must prioritize crop-cycle performance over marker-level response. SPAD, chlorophyll, MDA, ROS, antioxidant activity, ion fluxes, root traits, germination, and seedling biomass identify stress or early developmental sensitivity; they do not measure harvestable yield. Marker-level responses under controlled MP exposure should therefore not be used as evidence of productivity loss when harvestable yield is not measured [94]. Productivity inference requires mature biomass, fruit, grain, tuber, or storage-organ yield, marketable quality, or comparable crop-cycle variables measured at the relevant developmental stage. Harvestable yield and marketable or compositional quality provide stronger agronomic endpoints because they measure the crop outcome rather than an upstream stress response. Fruit-yield and fruit-quality endpoints in tomato, together with grain-quality and metabolomic endpoints in rice, provide stronger crop-relevance evidence than stress markers alone [53,115].

Contaminant-transfer studies must replace interaction evidence with same-system transfer evidence. Sorption, desorption, mobility assays, and field co-occurrence define contaminant interaction; they do not establish a vector effect. Vector-effect inference requires linked evidence of polymer–contaminant interaction, mobility or bioavailability, and plant-associated uptake, translocation, or tissue burden within the same exposure system. Co-exposure designs that quantify contaminant concentrations in plant tissues can support bounded transfer inference when the transfer pathway is measured directly, as shown for antibiotic or metal transfer under defined MP exposure systems [6,33]. Such evidence remains constrained by the exposure system, crop stage, and tissue compartment measured. Field correlations between MP abundance and contaminant concentration identify co-contamination scenarios, but they do not establish MP-mediated uptake without tissue-level transfer measurements [54].

Particle localization studies must separate surface association, entrapment, internal localization, and transport to harvestable compartments. Root adhesion, mucilage association, unvalidated fluorescence signals, or particle presence near vascular tissues should not be

treated as equivalent to internalization or edible-organ burden. Stronger designs combine validated localization, extraction-controlled analysis, surface–interior distinction, and, where feasible, mass-balance or tracer-based quantification. Storage-organ localization can support bounded edible-compartment occurrence under defined pot or greenhouse conditions, while mass-balance approaches strengthen tissue-burden interpretation when they separate associated from internalized particles [32,56]. Tissue-level visualization can strengthen localization inference, but seedling or simplified-system evidence remains mechanism-oriented until mature edible-organ burden is measured at crop stage [114,116].

Food-safety relevance requires an exposure-oriented layer beyond edible-compartment occurrence. Measured edible-tissue burden must be linked to surface–interior distinction, bioaccessibility, dietary exposure, contaminant or additive context, and risk-oriented interpretation. Estimated daily intake or hazard-index approaches strengthen exposure-oriented interpretation when they are grounded in measured edible-compartment burdens, but they do not replace toxicity, dose–response, or contextual exposure evidence required for formal human-health risk assessment [117]. These screening estimates are typically predicated on conservative assumptions of 100% bioavailability, an assumption that is unlikely to hold for large (>10 μm) or hydrophobic particles and that in vitro bioaccessibility studies have shown to substantially overestimate release [118–120]. Physiologically based toxicokinetic models are beginning to provide more realistic, size-dependent absorption estimates [121], but most EDI-based risk assessments remain screening-level tools rather than definitive exposure characterizations.

Evidence that MP particles carry pathogens or contaminants to edible surfaces supports a bounded contamination-pathway inference, not systemic infection, clinical risk, or generalized food-chain threat [55]. In this priority, the endpoint, not the severity of the observed response, sets the maximum defensible claim. The next roadmap priority is material realism: whether the particles, additives, mixtures, and co-contaminants used in experiments represent agricultural MP/NP residues.

3.4.5. *Mixed materials, aged particles, additives, and co-contaminants*

Material realism is not a checklist of more complex particles; it is a trade-off between field resemblance and attribution. Single pristine polymers remain useful when the claim is mechanistic and restricted to that material class. They become weak proxies when the claim concerns agricultural residues, because field-derived MP/NP materials are mixtures shaped by weathering, fragmentation, additive release, biofilm formation, and co-contaminant exposure. The design target is therefore not complexity itself, but attribution-preserving complexity: materials should approximate agricultural residues while the experiment still separates polymer identity, size, morphology, aging state, additive chemistry, and co-contaminant interactions.

Field-derived and aged materials sharpen agricultural relevance only when they are characterized as materials, not treated as generic "realistic plastics". Weathered mulch fragments, biosolid-derived residues, and multi-polymer assemblages can represent persistence, fragmentation, and transport more directly than uniform pristine particles, but their inferential value depends on descriptor quality. Polymer identity, size fraction, shape, mixture proportion, degradation state, and material source define the minimum information needed to interpret a material-realism claim. Without those descriptors, a mixture may resemble the field visually while remaining analytically opaque. Weathered mulch-film and legacy biosolid evidence can support persistence, fragmentation, and material-behavior inference, but they do not assign the response to a specific polymer or degradation pathway unless the design separates those components [35,45,53].

Additives and leachates shift the problem from particle realism to causal attribution. A response observed under exposure to agricultural film fragments cannot be assigned to the polymer backbone when particle structure, surface aging, additive release, and leachate chemistry remain bundled in the same treatment. Stronger designs separate these layers through factorial contrasts: particle-only versus leachate-only treatments, additive-free versus additive-bearing particles of the same polymer, and pristine versus weathered fragments under matched exposure conditions. Additive-release profiles from agricultural films show that polyethylene alone cannot represent the chemical behavior of all agricultural plastic residues, but additive-specific toxicity requires factorial attribution and endpoint-specific response data [122]. The same logic applies to conventional and biodegradable materials: comparative behavior under tested conditions should not be converted into inherent safety or hazard without separating physical and chemical contributions [123,124].

Co-contaminants add realism only when the design tests interaction rather than simply adding complexity. Metals, antibiotics, pesticides, pathogens, and organic contaminants may co-occur with agricultural plastics, but co-occurrence alone does not define the role of the plastic.

A robust co-exposure design must separate polymer-only, contaminant-only, combined, and untreated controls so that additive, synergistic, or antagonistic responses can be interpreted. This factorial structure is methodologically necessary for causal attribution, yet it is rarely implemented in practice; most studies report co-occurrence patterns or single-exposure responses without the factorial contrasts needed to disentangle polymer and contaminant contributions [54]. Even studies that include combined exposures often lack the appropriate factorial controls to distinguish additive effects from true interaction [72]. The factorial design should therefore be treated as a priority for future co-exposure research rather than as a description of the current evidence base. Field evidence of mixed polymers and cadmium identifies plausible co-contamination scenarios, whereas controlled co-exposures with antibiotics or biological contaminants can test interaction pathways when the polymer, contaminant, and receiving compartment are measured together [33,54,55]. The claim remains bounded to the tested material, exposure system, and endpoint class.

This final roadmap priority changes the design question from "which plastic was tested?" to "which material component supports the claim?" Future MP/NP soil–plant studies should move from generic pristine particles toward characterized field-derived or field-relevant materials, but they must preserve attribution through factorial contrasts and minimum material descriptors. Material realism strengthens the relevance of the exposure scenario only when it remains connected to analytical comparability, field-calibrated exposure, integrated mechanisms, and claim-aligned endpoints. The roadmap therefore shifts the field from testing plastics as generic particles toward building evidence chains in which exposure, material identity, mechanism, endpoint, and claim remain aligned.

4. Conclusions

MP/NP research in soil–plant systems has moved from occurrence documentation toward mechanistic interpretation, but its translation into agronomic inference remains constrained by a persistent mismatch between measured endpoints and claimed outcomes. The current literature supports mechanistic plausibility: MPs/NPs can alter soil physical properties, nutrient dynamics, microbial communities, plant physiological responses, contaminant behavior, and tissue-level particle interactions under defined conditions. These responses are informative biological and environmental signals. They do not, by themselves, establish yield loss, soil functional decline, contaminant-vector effects, food-safety relevance, human-health risk, or field-scale agronomic impact. The translational gap identified in this review therefore arises less from the absence of MP/NP-induced responses than from the escalation of proxy evidence beyond its inferential limit.

This review proposes an interpretive framework for separating particle occurrence, mechanistic response, microbial functional response, crop performance, contaminant transfer, edible-tissue relevance, and higher-level agronomic claims. The framework classifies inferential

strength rather than study quality. Its central rule is direct: each claim must stop at the strongest validated evidence layer available. Analytical validity determines whether the particle signal can be trusted; exposure realism determines whether the system can support agricultural interpretation; endpoint validity determines whether the measured response corresponds to the claim; and temporal, material, and design realism determine whether mechanistic evidence can move toward field-relevant inference. Under this framework, physiological markers do not establish productivity loss, taxonomic restructuring does not establish microbial functional response, sorption does not establish vector effects, tissue detection does not establish food-safety relevance or human-health risk, and long-term occurrence does not establish long-term agronomic impact.

Closing the translational gap requires redesigning MP/NP soil–plant studies around claim-aligned evidence chains rather than isolated responses. Future studies should connect validated particle identification with field-calibrated exposure, temporally structured or legacy-paired designs, integrated soil–microbiome–plant endpoints, crop-cycle performance variables, edible-compartment measurements, same-system contaminant-transfer evidence, and attribution-preserving material realism. This does not require every study to address every claim; it requires each study to align its analytical method, exposure scenario, material type, endpoint class, temporal scale, and claim scope. Mechanistic studies remain essential, but their conclusions should remain mechanistic unless the design adds the evidence required for agronomic, productivity, transfer, or food-safety-relevance interpretation.

The contribution of this review is not to classify MPs/NPs as uniformly harmful or harmless in agricultural systems, but to define the evidentiary conditions under which different claims become defensible. The field should now move beyond asking whether MPs/NPs can induce responses under controlled conditions and focus on whether those responses are analytically validated, exposure-aligned, endpoint-matched, temporally structured, and materially attributable. Progress will depend on evidence chains in which particle identity, exposure scenario, material realism, biological mechanism, endpoint class, and claim scope remain aligned. Closing the translational gap requires not merely more studies, but better-configured evidence.

Ethical statement – studies in humans and animals

Ethics approval was not required because this study did not involve human participants, animals, or identifiable personal data.

Generative AI statement

Generative AI tools were used solely to facilitate translation, refine scientific language, and ensure clarity of expression. All of the resulting text was critically reviewed, edited, and approved by the authors, who assume full responsibility for the manuscript.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2026.103120.

Data availability

Data will be made available on request.

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