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Review Article

Biotechnological Perspectives on the Environmental Fate and Ecological Risks of Engineered Metal and Metal Oxide Nanoparticles in Agroecosystems

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Abstract

Engineered metal and metal oxide nanoparticles are increasingly promoted as nanofertilizers, nanopesticides, and soil amendments, yet their environmental fate and ecological risks in agroecosystems remain contested. This critical review synthesizes peer-reviewed evidence from a biotechnological perspective, integrating material transformation, microbial ecology, plant interactions, and risk assessment rather than treating them as separate domains. Microbial redox transformation, biofilm formation, and rhizosphere processes mediate aggregation, dissolution, and bioavailability, so nanoparticle behavior cannot be predicted from abiotic chemistry alone. However, most ecotoxicological evidence derives from pristine particles, simplified media, short exposures, and unrealistically high concentrations, while transformation products, mixture effects with conventional agrochemicals, and repeated low-dose agricultural inputs are seldom represented. Current risk frameworks, derived from chemical paradigms, treat biological mediation as context rather than as a determinant of risk, and regulatory oversight remains fragmented. Biotechnological tools, including metagenomic monitoring, biosensors, and bioremediation, show promise, but most remain laboratory-bound, and remediation may immobilize rather than remove contaminants. We argue that the long-term ecological safety of engineered metal and metal oxide nanoparticles in agroecosystems remains unproven not because evidence is absent but because it is insufficiently integrated, field-relevant, and critically interpreted, and we propose research priorities, governance needs, and precautionary management recommendations for sustainable agriculture.

Keywords: Bioremediation; Ecotoxicology; Engineered nanoparticles; Nano-enabled agriculture; Risk governance; Soil microbial ecology

1. Introduction

Engineered metal and metal oxide nanoparticles (ENPs) have moved rapidly from laboratory innovation into agricultural practice, where they are promoted as nanofertilizers, nanopesticides, soil amendments, and delivery vehicles for micronutrients and active ingredients (Ma, Li, Zhu, Li, Qu, Sun, *et al.*, 2026; Vishwakarma *et al.*, 2023). Their high surface-area-to-volume ratio, tunable surface chemistry, and redox activity underpin desired agronomic functions, including improved nutrient use efficiency, pest suppression, and stress tolerance (Anuta *et al.*, 2025). These same properties, however, create legitimate concerns about persistence, transformation, bioavailability, and unintended effects in soil–plant–water systems. Agroecosystems are particularly challenging because they are biologically active, temporally variable, and managed for production; ENPs introduced through irrigation, foliar sprays, seed coatings, or biosolids may undergo aggregation, dissolution, sulfidation, adsorption, and plant or microbial transformation (Ahmed *et al.*, 2021; Hussain, Javed, *et al.*, 2026; Xiao *et al.*, 2026). Such processes alter exposure and toxicity in ways that cannot be inferred from pristine material properties alone.

The scientific literature on ENP fate and effects has expanded substantially, yet it remains fragmented across materials science, soil chemistry, plant physiology, microbial ecology, and ecotoxicology. Risk assessments frequently depend on short-term single-species tests and standardized media that poorly represent field soils, rhizosphere processes, and microbial community dynamics (McKee & Filser, 2016; X. Wang *et al.*, 2026; X. Wu *et al.*, 2026). Conversely, biotechnological applications such as bioremediation, biomonitoring, and microbially assisted phytoremediation are often discussed separately from hazard assessment, even though they share mechanistic ground with ENP fate and ecological risk (Motrescu & Luchian, 2026; Raklami *et al.*, 2022). This separation limits the development of integrated risk-management strategies. A critical synthesis is therefore needed to examine how biotechnological processes both influence ENP fate and offer tools for monitoring, mitigating, and governing risks in agroecosystems. An integrated assessment is therefore needed for evaluating the environmental fate and ecological risks of ENPs from a biotechnological perspective, with attention to sources, transformation pathways, ecotoxicological outcomes, and practical interventions. In doing so, it seeks to distinguish robust evidence from assumptions, highlight methodological limitations, and frame a research and governance agenda that is relevant to applied environmental biotechnology. A further complication is that agricultural soils receive repeated low-dose inputs rather than single high-dose exposures, and these inputs interact with fertilization, tillage, crop rotation, and microbial community succession (Gupta *et al.*, 2022). These management realities are seldom captured in experimental designs, creating uncertainty about long-term ecological consequences and the reliability of current risk thresholds. Addressing this uncertainty requires approaches that connect material transformation, biological response, and agronomic practice rather than treating them as separate domains.

Engineered metal and metal oxide nanoparticles are increasingly positioned as solutions to pressing agronomic problems, including nutrient deficiency, pest pressure, and abiotic stress. Zinc oxide, copper oxide, titanium dioxide, silver, and iron oxide nanoparticles illustrate the diversity of materials entering soils through nano-enabled fertilizers, pesticides, and amendments (Bratovcic *et al.*, 2023; Farooq *et al.*, 2022; R. Sharma & Kumar, 2024). Their intended functions depend on controlled reactivity and mobility, yet the same characteristics determine unintended interactions with soil biota, crops, and water resources. The rationale for focusing on metal and metal oxide nanoparticles is therefore twofold: they represent a large and expanding share of agricultural nanomaterials, and their fate is strongly mediated by biogeochemical and biological processes that biotechnology is well placed to interrogate (Carrapiço *et al.*, 2023; Yugay & Shkryl, 2026). Microbial communities drive redox transformations, aggregation, dissolution, and organic matter interactions that modify nanoparticle speciation and bioavailability (Haydar *et al.*, 2025). Plants and associated microbes also influence uptake, translocation, and trophic transfer. Ignoring these biological mediators produces risk assessments that are mechanistically shallow and poorly predictive. This limitation is especially consequential in managed soils where microbial activity, organic amendments, and crop cycles alter exposure dynamically across seasons in complex ways (Das *et al.*, 2025). A biotechnological perspective is also warranted because the tools of environmental biotechnology, including microbial community profiling, biomarker development, biosorption, and bioremediation, can support both hazard diagnosis and risk mitigation.

This review critically synthesizes peer-reviewed evidence on the environmental fate and ecological risks of ENPs in agroecosystems from a biotechnological perspective. Its objectives are to evaluate sources and transformation pathways, assess ecotoxicological and trophic effects, examine biotechnology-mediated monitoring and mitigation options, and identify research and governance priorities. The approach integrates material fate, microbial

ecology, plant interactions, and risk assessment rather than treating them separately.

2. Sources, Environmental Fate, and Biotechnological Drivers of Nanoparticle Behavior in Agroecosystems

Engineered metal and metal oxide nanoparticles enter agroecosystems through multiple deliberate and incidental routes that vary in space and time. Nano-enabled fertilizers, pesticides, seed treatments, and soil amendments constitute primary deliberate sources, while biosolids, irrigation water, atmospheric deposition, and weathering of nano-coated materials contribute incidental inputs (Acevedo & Govan, 2026; Shukla *et al.*, 2026). Exposure pathways include soil pore water, rhizosphere solutions, plant surfaces, and drainage networks, with the relative importance of each pathway varying by crop system, application method, soil texture, organic matter content, and hydrology (Husak *et al.*, 2026; Y. Tao *et al.*, 2026). Because agricultural soils receive repeated low-dose inputs, episodic and cumulative exposures differ markedly from the single high-dose scenarios common in laboratory studies (Wan *et al.*, 2024). This mismatch complicates extrapolation from ecotoxicological tests to field conditions and underscores the need to characterize sources and pathways in management-relevant contexts. Moreover, the co-occurrence of nanoparticles with conventional agrochemicals and organic amendments can alter exposure dynamics through competitive sorption, complexation, and changes in soil solution chemistry (Z. Tao *et al.*, 2023). Such interactions are rarely quantified but are central to realistic risk assessment.

Biotechnological drivers shape nanoparticle fate and bioavailability through microbial metabolism, biofilm formation, and plant–microbe interactions. Microorganisms catalyze redox transformations that alter metal speciation, solubility, and toxicity, while extracellular polymeric substances promote aggregation or stabilization depending on solution chemistry (Glasauer *et al.*, 2023). Root exudates modify rhizosphere pH, redox potential, and dissolved organic carbon, thereby influencing nanoparticle dissolution and plant uptake (Leszczuk & Zając, 2026). These biological processes are dynamic and respond to agricultural management, including fertilization, irrigation, and crop rotation. Consequently, the fate of nanoparticles in agroecosystems cannot be predicted from abiotic chemistry alone; biotic mediation must be incorporated into exposure and risk models (A. Sharma *et al.*, 2026). Recognizing these drivers also opens avenues for biotechnological intervention, from biomonitoring to bioremediation. However, the mechanistic understanding of microbially mediated transformation remains uneven across nanoparticle types and soil conditions. Many studies rely on simplified microbial communities or sterile media, limiting inference about field-scale persistence and bioavailability. A more rigorous integration of microbial ecology with nanomaterial fate modeling is therefore essential for realistic risk assessment.

2.1. Agricultural Sources, Exposure Pathways, and Transformation Processes of Metal and Metal Oxide Nanoparticles

Agricultural sources of metal and metal oxide nanoparticles are diverse and expanding. Nanofertilizers formulated with zinc oxide, iron oxide, or copper oxide are applied to soils or foliage to correct micronutrient deficiencies and improve yield (Kumar *et al.*, 2025). Nanopesticides containing silver, copper, or titanium dioxide are used for pathogen and pest control (Shandila *et al.*, 2025). Seed coatings and soil amendments introduce nanoparticles directly into the rhizosphere, while biosolids and composts derived from wastewater treatment represent indirect but substantial inputs (do Espirito Santo Pereira *et al.*, 2021; Haider *et al.*, 2026). Irrigation with treated wastewater and atmospheric deposition further contribute to diffuse contamination. Exposure pathways follow these inputs: nanoparticles may remain in soil, partition to pore water, associate with soil organic matter and clay minerals, be taken up by roots, translocate to shoots, or be transported via runoff and leaching (Djanaguiraman *et al.*, 2024). The relative significance of each pathway depends on nanoparticle properties, soil characteristics, and agronomic practices. Critically, most field-level exposure estimates rely on modeled rather than measured concentrations, introducing uncertainty into risk characterization. Figure 1 summarizes the principal agricultural sources, exposure pathways, and transformation processes and highlights where field-level measurement remains absent.

Once introduced, nanoparticles undergo transformation processes that alter speciation, mobility, and toxicity. Aggregation reduces particle number concentration and may decrease bioavailability, although clusters can still interact with biota (Singh *et al.*, 2023). Dissolution releases metal ions that are often more toxic than parent particles, particularly for zinc oxide and copper oxide (Kochar *et al.*, 2022). Sulfidation under anaerobic or flooded conditions converts silver and copper nanoparticles to less soluble metal sulfides, modifying persistence and ecotoxicity (O'Keefe & Haynes, 2024). Adsorption to mineral surfaces and organic matter immobilizes nanoparticles but may also facilitate colloidal transport. Redox and photochemical transformations further change surface chemistry and reactivity (Bao *et al.*, 2022). These processes are

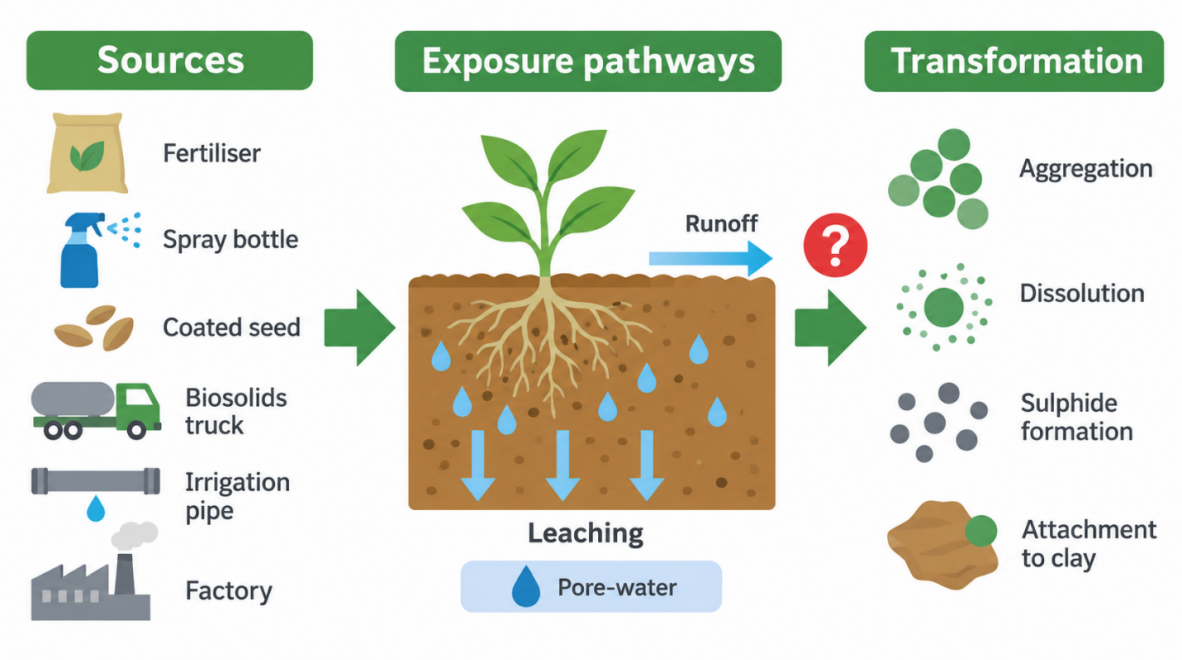

Figure 1. Agricultural sources, exposure pathways, and transformation processes of metal and metal oxide nanoparticles. Schematic of the principal deliberate and incidental agricultural sources of engineered metal and metal oxide nanoparticles, the exposure pathways that connect these sources to soil, pore water, crops, and drainage networks, and the key transformation processes (aggregation, dissolution, sulfidation, and adsorption) that modify speciation and bioavailability. The question mark denotes the point at which field-measured concentrations are largely unavailable and modeled estimates are relied upon.

interdependent and influenced by soil pH, redox potential, ionic strength, and organic carbon content. A critical limitation is that many transformation studies use simplified media and short durations, whereas agricultural soils are heterogeneous and seasonally variable. Consequently, long-term nanoparticle fate in agroecosystems remains poorly constrained, and transformation products are rarely incorporated into exposure and ecological risk assessments. Table 1 synthesizes, for the principal nanoparticle classes, their agricultural applications, dominant transformation pathways, principal ecological risks, and biotechnological relevance, providing a material-specific comparison.

2.2. Biotic and Biotechnological Factors Governing Nanoparticle Fate, Bioavailability, and Persistence

Biotic factors govern nanoparticle fate and bioavailability through microbial and plant-mediated processes that are central to agroecosystem function. Soil microorganisms catalyze redox transformations, produce chelators and siderophores, and form biofilms that alter nanoparticle aggregation, dissolution, surface charge, and metal speciation (Li *et al.*, 2025). Microbial community composition shifts in response to nanoparticle exposure, with consequences for nutrient cycling, soil health, and ecosystem services that extend beyond direct toxicity (Chowdhury & Ghosh, 2025). Mycorrhizal fungi and rhizosphere bacteria modify root exudation and nutrient uptake, thereby influencing nanoparticle bioavailability and plant accumulation (Zhang *et al.*, 2024). Earthworms and other soil fauna contribute to particle redistribution and incorporation into aggregates over seasonal cycles (J. Wu *et al.*, 2024). These biotic interactions are spatially structured at the rhizosphere and aggregate scale, and they respond rapidly to management practices such as tillage, irrigation, organic amendment, and crop rotation. A critical gap is that most mechanistic studies isolate single organisms or processes, whereas the field fate depends on interacting communities and trophic networks. Consequently, biotic drivers are often acknowledged but rarely quantified in risk models.

Biotechnological approaches both illuminate and influence nanoparticle fate in agroecosystems. Molecular tools such as quantitative polymerase chain reaction, metagenomics, and metatranscriptomics reveal microbial responses to nanoparticle exposure and identify taxa and functions associated with transformation or tolerance (Metch *et al.*, 2018). Biosensors and biomarker-based assays offer rapid detection of nanoparticle-induced

Table 1. Comparative synthesis of agriculturally relevant engineered metal and metal oxide nanoparticles: applications, dominant transformation pathways, principal ecological risks, and biotechnological relevance

Nanoparticle class	Principal agricultural application	Dominant fate and transformation process	Principal ecological concerns and potentially affected receptors	Biotechnological relevance
ZnO	Nanofertilizer for Zn biofortification; antifungal seed and foliar treatments	Rapid dissolution to Zn^{2+}; pH-dependent speciation; adsorption to clay and organic matter	Phytotoxicity and microbial community shifts at elevated Zn^{2+}; soil enzyme inhibition	Zn-mobilizing and Zn-tolerant microbial consortia as bioavailability indicators; biosorption for Zn recovery
CuO and other Cu-based nanoparticles	Nanopesticide and bactericide; soil amendment in Cu-deficient soils	Slow dissolution with particle persistence; complexation with dissolved organic matter; redox cycling	Chronic soil invertebrate toxicity; earthworm and collembolan decline; inhibition of nitrification	Cu-resistance gene profiling and metagenomic monitoring; bacterial biosorption and biomineralization
Ag	Antimicrobial coating of seeds, irrigation systems, and storage materials	Sulfidation to Ag_2S under anaerobic conditions; chloride complexation; aggregation	Microbial community suppression; disruption of litter decomposition and nutrient cycling	Biosensor-based detection of Ag^+; microbial community resilience as a monitoring endpoint
TiO_2	Photocatalytic pesticide formulations; UV-protective films and coatings	Minimal dissolution; aggregation and sedimentation; limited sulfidation; photo-induced radical generation	Oxidative stress in aquatic organisms via runoff; disruption of detrital food webs	Photocatalytic–biological hybrid treatment; microbial toxicity biomarkers under UV exposure
Fe_3O_4 and γ-Fe_2O_3	Micronutrient delivery; magnetic carriers for targeted agrochemical release	Reductive dissolution and Fe^{2+} release; biogenic magnetite formation; organic matter coating	Generally low intrinsic hazard; indirect effects via Fe speciation and phosphorus sorption	Strongest biotechnological relevance of all classes; magnetically recoverable biosorbents and nanoparticle-assisted bioremediation
CeO_2	Growth-promoting soil amendment; antioxidant and stress-mitigation agent	Low dissolution; surface redox cycling between Ce^{3+} and Ce^{4+}; strong aggregation in soil	Antioxidant interference with root signaling; uncertain long-term soil persistence	Microbial oxidative-stress reporters; enzyme-mimetic behavior relevant to soil redox monitoring
Al_2O_3 and SiO_2 composites	Nanocarriers for nutrient and pesticide delivery; soil conditioning agents	Predominantly physical fate: aggregation, deposition, and pore clogging; negligible dissolution	Physical effects on root elongation and microbial habitat structure; colloidal transport to drainage	Silica-encapsulated microbial inoculants; biofilm–particle interactions as a delivery design variable

stress and can be deployed for field monitoring, although validation remains limited (Khan *et al.*, 2026). Bioremediation strategies exploit microbial biosorption, enzymatic reduction, and phytoremediation assisted by plant growth-promoting bacteria to immobilize or remove metal nanoparticles and released ions. Engineered microbial consortia and biofilm-based systems show promise for stabilizing nanoparticles in contaminated soils, but field-scale evidence is sparse (Karnwal *et al.*, 2025). However, these applications are rarely evaluated under realistic agricultural field conditions, and the long-term ecological consequences remain uncertain. A critical perspective must therefore distinguish demonstrated mechanisms from optimistic extrapolation and must also consider the trade-offs between remediation efficacy and its potential long-term effects on soil health and microbial communities. Integrating biotechnological monitoring and mitigation with fate and risk assessment would strengthen both environmental protection and sustainable agricultural practice across diverse agroecosystems (Pedrino & Lacava, 2026). Figure 2 illustrates how microbial and plant-mediated processes, together with the biotechnological tools used to interrogate them, govern nanoparticle fate and bioavailability in agricultural soils.

3. Ecological Risks and Biotechnology-Mediated Interactions of Metal and Metal Oxide Nanoparticles

The ecological risks posed by ENPs in agroecosystems cannot be adequately characterized through toxicity assays

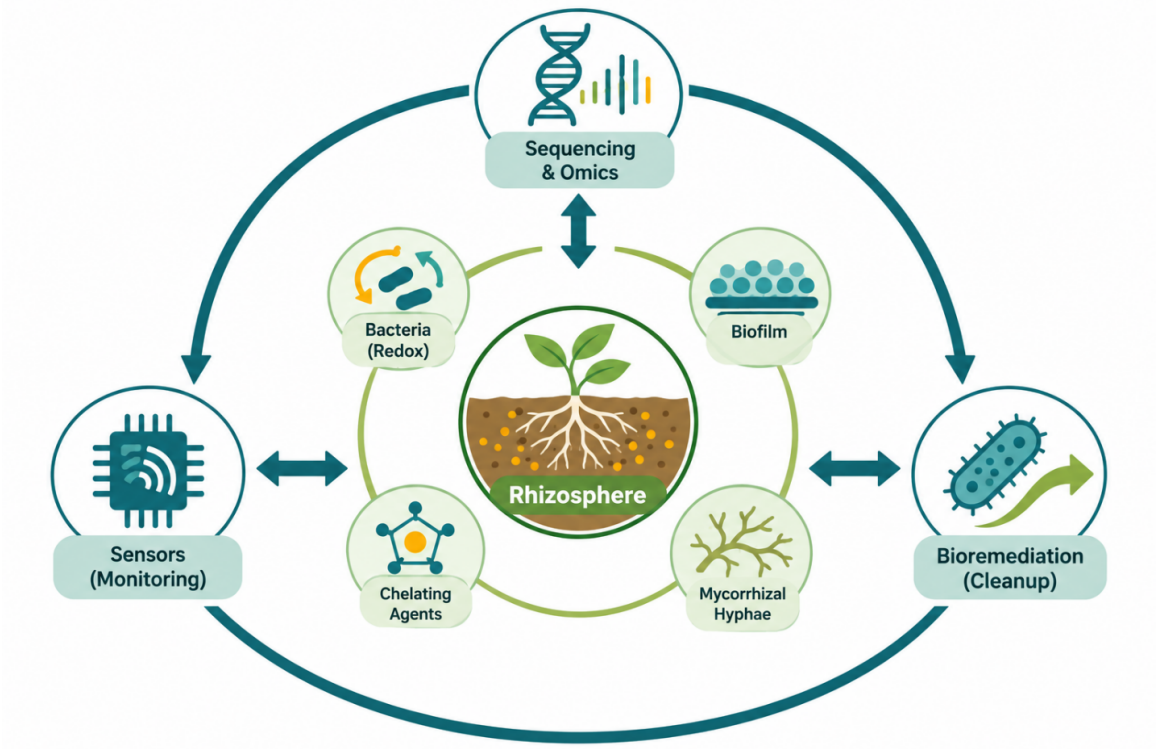

Figure 2. Biotic and biotechnological drivers governing nanoparticle fate, bioavailability, and persistence. Conceptual hub-and-spoke diagram of the biotic processes that mediate nanoparticle fate in agroecosystems, including microbial redox transformation, biofilm formation, siderophore-mediated complexation, and mycorrhizal and rhizosphere interactions, together with the biotechnological tools used to observe and exploit these processes. Double-headed arrows indicate that biotechnological interventions both respond to and modify biotic mediation of nanoparticle behavior.

alone. Biotic interactions modify exposure and effect, and some interactions are biotechnology-mediated, creating feedbacks that current risk frameworks fail to capture (Kalra *et al.*, 2024). Microbial transformation may reduce toxicity through sulfidation or immobilization, yet the same processes can produce nanoparticulate sulfides with poorly understood effects on soil communities (Xu *et al.*, 2023). Plant-microbe associations may enhance or restrict uptake, altering trophic transfer in ways that standard single-species tests do not represent (Oyewole *et al.*, 2026). A critical reading reveals that many risk conclusions rest on short-term experiments with pristine particles in simplified media, which cannot account for aged nanoparticles, transformation products, or repeated low-dose agricultural inputs (Islam, 2025). Consequently, the assumption that laboratory-derived hazard thresholds protect field ecosystems remains weakly supported. Biotechnology enters this discussion not only as a source of monitoring and remediation tools but also as a driver of ecological interactions that can amplify or attenuate risk (Baruwa *et al.*, 2026). Ignoring this dual role produces risk assessments that appear precise but are mechanistically incomplete.

A critical evaluation must therefore ask whether biotechnology-mediated interactions are incorporated into risk assessment or merely acknowledged in discussion sections. In most frameworks, they are not. Ecological risk assessment for nanoparticles typically follows chemical risk paradigms that emphasize exposure concentration and dose-response, while neglecting microbial community dynamics, biofilm formation, and rhizosphere processes that determine actual bioavailability (Chen *et al.*, 2022; Scott-Fordsmand *et al.*, 2017). This omission is not trivial; it can misclassify risk in both directions. For example, microbial immobilization may lower exposure but also concentrate metals in biofilms that are subsequently consumed by soil fauna, creating a trophic pathway absent from standard models (Kuyukina *et al.*, 2026). Conversely, plant growth-promoting bacteria may alleviate nanoparticle stress while facilitating metal accumulation in edible tissues, a trade-off rarely quantified (Y. Wang *et al.*, 2022). The biotechnological perspective thus exposes a fundamental weakness in current risk assessment frameworks, as they treat biological interactions as context rather than as determinants of risk. Until risk assessment explicitly incorporates these interactions,

conclusions about the ecological safety of nanoparticles in agroecosystems will remain provisional and potentially misleading for regulatory and management decisions.

3.1. Ecotoxicological Effects, Trophic Transfer, and Risk Assessment Frameworks in Agroecosystems

Ecotoxicological studies of metal and metal oxide nanoparticles in agroecosystems have generated an uneven evidence base. Many reports document oxidative stress, membrane damage, and growth inhibition in plants and soil invertebrates, yet the experimental conditions often bear little resemblance to field agriculture (Ma, Li, Zhu, Li, Qu, Zhou, *et al.*, 2026; Rastogi *et al.*, 2017; F. Wang *et al.*, 2024). Test concentrations exceed environmentally realistic levels by orders of magnitude, exposure durations are short, and particles are rarely aged or transformed before testing. These design choices inflate apparent hazard while obscuring the subtle, chronic effects that matter for ecological risk. Trophic transfer is particularly understudied. Nanoparticles or released ions may accumulate in roots and translocate to shoots, but whether they move to herbivores, pollinators, or higher predators in agricultural food webs remains poorly quantified (Servin *et al.*, 2017; Z. Wang *et al.*, 2024). Microbial grazing and detrital pathways receive less attention, despite their central role in soil food webs. A critical assessment must acknowledge that ecotoxicological evidence is stronger for acute, direct toxicity than for chronic, indirect, and trophic effects in agroecosystems.

Risk assessment frameworks for nanoparticles in agriculture remain largely derivative of chemical risk paradigms (Feng *et al.*, 2026). They emphasize external exposure concentration, dose-response relationships, and standardized test endpoints, while treating soil biology as a static backdrop. This is a critical weakness because bioavailability and toxicity are mediated by microbial activity, organic matter dynamics, and rhizosphere chemistry, all of which vary with management (Ali *et al.*, 2026). Frameworks also rarely account for transformation products, mixture effects with conventional agrochemicals, or repeated low-dose inputs over multiple seasons. The resulting risk estimates may be conservative in some cases but insufficiently protective in others, and their uncertainty is seldom communicated transparently. Moreover, regulatory frameworks have not kept pace with the diversity of nano-enabled agricultural products entering the market (Pedrino & Lacava, 2026). A critical perspective must question whether current risk assessment approaches are fit for purpose in agroecosystems. Figure 3 presents the trophic transfer pathways and framework gaps that together explain why current risk assessment may misclassify nanoparticle hazard in agroecosystems.

3.2. Biotechnological Monitoring, Bioremediation, and Mitigation Strategies for Nanoparticle Contamination

Biotechnological tools for monitoring nanoparticle contamination in agroecosystems have advanced considerably, but their practical deployment in agricultural soils remains limited. Metagenomic and metatranscriptomic approaches can reveal microbial community shifts and functional responses to nanoparticle exposure, offering mechanistic insight beyond conventional toxicity endpoints (Chowdhury & Ghosh, 2025). Biosensors and biomarker assays promise rapid, field-deployable detection, yet most remain validated only under controlled laboratory conditions (Abdelhamid *et al.*, 2025). The gap between proof-of-concept and routine monitoring is substantial and rarely acknowledged in optimistic reviews. Bioremediation strategies, including microbial biosorption, enzymatic reduction, and phytoremediation assisted by plant growth-promoting bacteria, are frequently presented as solutions to nanoparticle contamination (Karnwal *et al.*, 2024). However, field-scale evidence is sparse, and many studies use artificially contaminated soils with unrealistically high metal concentrations. The efficacy of bioremediation under realistic low-dose, repeated-input agricultural conditions is largely unknown. Moreover, bioremediation may immobilize metals temporarily without removing them, creating a persistent legacy risk if land use changes (Zheng *et al.*, 2025). A critical evaluation must therefore distinguish between demonstrated mechanisms and speculative applications, and must demand field validation before bioremediation is promoted as a practical management option for nanoparticle-contaminated agroecosystems.

Mitigation strategies for nanoparticle contamination extend beyond bioremediation to include biochar amendments, microbial consortia, and engineered biogeochemical barriers (Hammami *et al.*, 2026). These approaches are often evaluated in isolation, yet their effectiveness depends on soil type, crop system, and nanoparticle speciation. A critical reading of the literature reveals a tendency to overstate mitigation potential based on short-term laboratory results. For example, biochar may sorb metal nanoparticles and reduce bioavailability, but it can also alter soil pH and microbial communities in ways that produce unintended effects (Hou & Li, 2026). Microbial consortia designed to immobilize metals may compete with native microbiota or transfer resistance genes, raising ecological concerns that are seldom addressed (Qattan, 2025). Furthermore, mitigation technologies are rarely assessed for their own environmental footprint, including energy use, material production, and long-term fate of immobilized contaminants (Dharsandia *et*

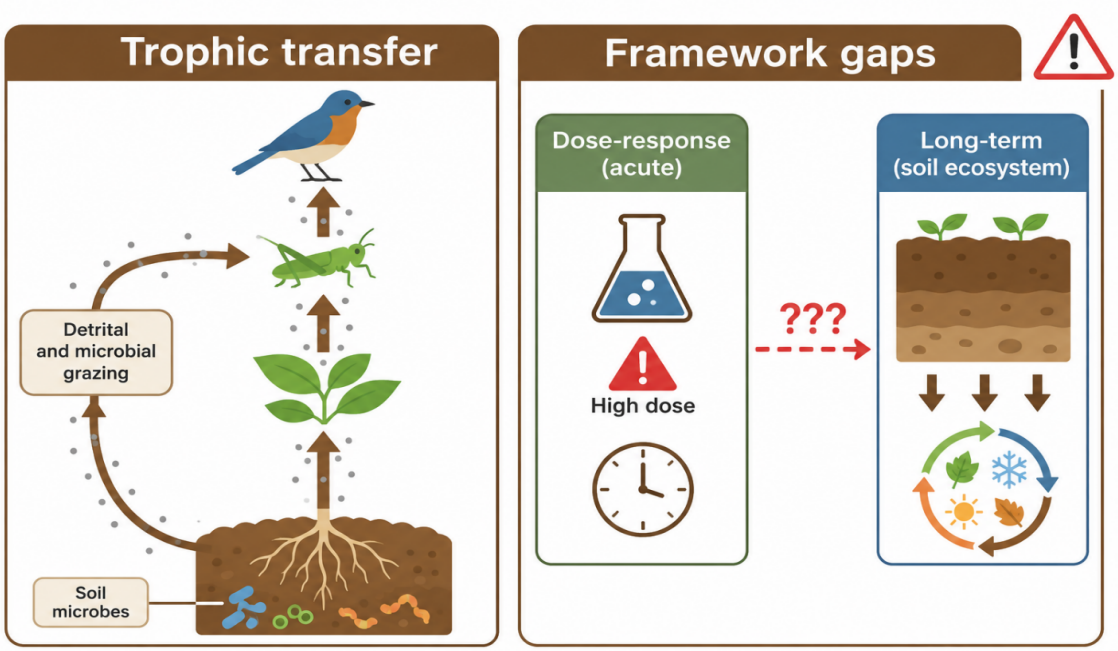

Figure 3. Ecotoxicological effects, trophic transfer pathways, and gaps in risk assessment frameworks. Dual-panel schematic contrasting the trophic transfer pathways through which metal and metal oxide nanoparticles may move within agricultural food webs with the mismatch between standardized laboratory test conditions and field-realistic agricultural exposure. The broken arrow and question marks highlight the extrapolation gap that current risk assessment frameworks do not resolve.

al., 2026). The biotechnological perspective thus demands an honest appraisal of trade-offs. Mitigation should not be framed as a substitute for precautionary nanoparticle design and responsible use. Instead, it should be integrated into a risk-management hierarchy that prioritizes avoidance, minimizes exposure, and uses biotechnological interventions where benefits outweigh ecological costs in agroecosystems. Figure 4 summarizes the principal biotechnology-mediated strategies for monitoring, remediating, and mitigating nanoparticle contamination together with the trade-offs that a critical appraisal must confront.

4. Future Perspectives and Practical Recommendations

Future perspectives on ENPs in agroecosystems must move beyond incremental calls for more research. The critical issue is not the absence of studies but weak integration and limited field relevance. Recommendations should prioritize realistic exposure scenarios, long-term monitoring, and explicit incorporation of biological mediation into risk assessment. Yet such recommendations are frequently repeated without confronting why they remain unimplemented. Funding rewards novel material synthesis over unglamorous field validation, and regulatory agencies lack the capacity to evaluate transformation products or mixture effects (Zeng *et al.*, 2025). A credible agenda must address these constraints rather than assuming better science alone will drive change. Biotechnology offers genuine opportunities, including microbial monitoring and bioremediation, but these should not be oversold as substitutes for precautionary design and responsible use (Musa *et al.*, 2026). The practical recommendation is to treat nanoparticles as part of a broader agrochemical load and to evaluate their risks cumulatively, across seasons and management regimes. This requires interdisciplinary collaboration and transparent uncertainty communication. Without such changes, future perspectives will remain rhetorical, and practical recommendations will continue to circulate without altering agricultural practice or environmental protection. The field needs fewer aspirational statements and more honest appraisal of what current evidence can and cannot support for sustainable agroecosystems.

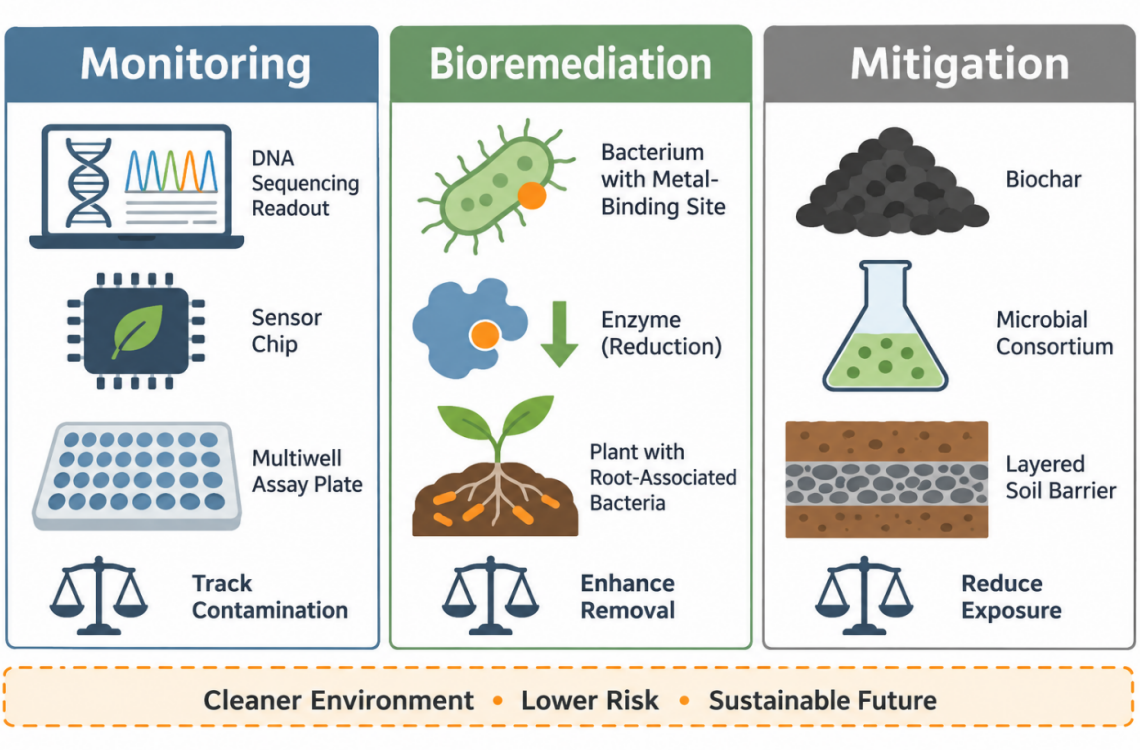

Figure 4. Biotechnology-mediated monitoring, bioremediation, and mitigation strategies and their trade-offs. Comparative schematic of biotechnology-mediated monitoring, bioremediation, and mitigation strategies proposed for nanoparticle contamination in agroecosystems, with each strategy paired with its principal critical trade-off. The dashed band emphasizes that all three categories remain insufficiently validated under field-realistic, low-dose, repeated-input agricultural conditions.

4.1. Research Priorities, Methodological Gaps, and Emerging Biotechnological Opportunities

Research priorities must target the methodological gaps that undermine confidence in nanoparticle risk assessment. The most serious gap is the scarcity of long-term field studies using aged particles under realistic agricultural inputs. Most mechanistic work relies on pristine nanoparticles, short exposures, and simplified media, producing findings that cannot be extrapolated to heterogeneous soils and seasonal management (Ali *et al.*, 2026; Hussain, Nauman, *et al.*, 2026). A second gap concerns transformation products, rarely identified or tested despite evidence that sulfidation and dissolution alter hazard. Emerging biotechnological opportunities, including metagenomic monitoring and biofilm-based remediation, remain largely laboratory-bound. The critical question is whether these tools can be validated and deployed at farm scale in agricultural soils without creating new ecological risks. Research should also address trophic transfer and mixture effects with conventional agrochemicals, both neglected relative to direct plant toxicity. Funding should shift from novel particle synthesis toward field validation and long-term monitoring, even though such work is less publishable and less attractive to sponsors and funding agencies. Without this shift, biotechnological opportunities will remain demonstrations rather than practical tools. Methodological standardization across laboratories is equally necessary for cross-study comparability. The field needs coordinated multi-site studies integrating fate, exposure, and ecological effect under real management conditions. Only then can research priorities support credible, robust risk assessment and meaningful biotechnology applications in agroecosystems. Figure 5 presents an integrated framework that links the research priorities, governance needs, and management recommendations.

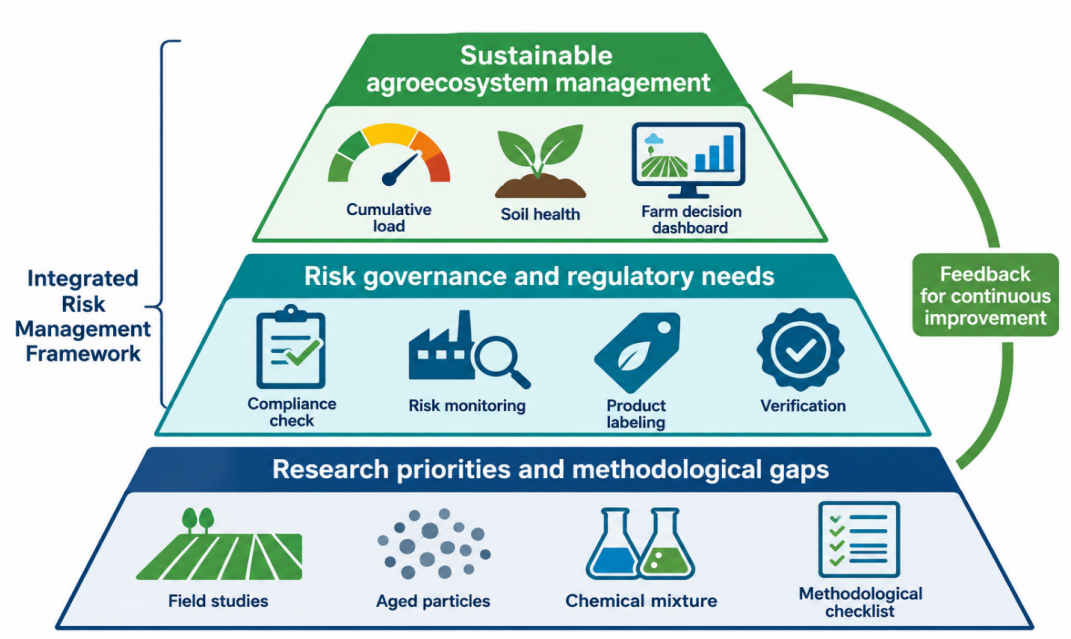

Figure 5. Integrated framework linking research priorities, risk governance, and sustainable management of nano-enabled agriculture. Integrated three-tier framework for the responsible management of engineered metal and metal oxide nanoparticles in agroecosystems, linking field-relevant research priorities at the base to enforceable risk governance in the middle and sustainable management practice at the apex. The feedback arrow represents adaptive governance, and the side bracket indicates the precautionary hierarchy that underpins the recommendations of this review.

5. Conclusion

This review has critically examined the environmental fate and ecological risks of ENPs in agroecosystems from a biotechnological perspective. The evidence base is substantial but uneven. Most studies rely on pristine particles, simplified media, short exposures, and concentrations far above field-realistic levels. Consequently, claims about persistence, bioavailability, and long-term ecological effects rest on weak foundations. Transformation processes such as dissolution, sulfidation, and aggregation are recognized but rarely incorporated into risk assessment. The repeated low-dose inputs characteristic of agricultural practice remain poorly represented. A critical reading therefore cautions against assuming that laboratory-derived hazard thresholds protect field ecosystems. The field has accumulated data without achieving the integration needed to support confident risk conclusions. This imbalance is not merely technical; it reflects funding priorities and publication incentives that reward novelty over validation. Biotechnological interactions complicate risk assessment in ways that current frameworks do not capture. Microbial transformation, biofilm formation, and rhizosphere processes mediate exposure and toxicity, yet they are treated as context rather than determinants of risk. Biotechnological monitoring and bioremediation tools show promise but remain largely laboratory-bound and rarely validated under realistic agricultural conditions. Bioremediation may immobilize rather than remove contaminants, creating legacy risks. Risk assessment frameworks remain derivative of chemical paradigms and neglect transformation products, mixture effects, and trophic transfer. Regulatory oversight is fragmented, underfunded, and reliant on voluntary data. The critical conclusion is that current governance does not match the complexity of nanoparticle behavior in agroecosystems. Absence of evidence continues to be misread as evidence of safety, and biotechnological optimism often substitutes for precautionary action. This pattern is familiar from earlier agricultural technologies and should not be repeated uncritically.

Practical recommendations must therefore prioritize enforceable regulation, mandatory field-scale data, post-market surveillance, and transparent labeling. These are not novel recommendations, but their persistent non-implementation reveals structural constraints that better science alone will not resolve. Funding incentives favor novel synthesis over unglamorous field validation. Regulatory capacity is weak, and international harmonization is limited. Biotechnology can contribute to monitoring and mitigation, but it should not be framed as

a substitute for precautionary design and responsible use. Sustainable management requires integrating nanoparticles into cumulative agrochemical load assessments and soil health indicators. The overall conclusion is that the ecological safety of metal and metal oxide nanoparticles in agroecosystems remains unproven, not because evidence is absent, but because the evidence is insufficiently integrated, field-relevant, and critically interpreted. Honest uncertainty communication and adaptive governance are essential.

Author Contributions

All authors contributed to the study conception and design. The first draft of the manuscript was written by all authors, and they commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflict of Interest

None of the authors have reported a conflict of interest.

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