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The Environmental Paradox of Nanobioinoculants: Balancing Agricultural Benefits against Ecosystem Risks

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Abstract

Nanobioinoculants hybrid systems combining engineered nanoparticles with beneficial microorganisms represent a promising frontier in sustainable agriculture. These nano-enabled formulations improve nutrient delivery, enhance crop resilience, and reduce chemical input, yet their environmental safety remains uncertain due to potential nanoparticle toxicity, soil microbiome disruption, and trophic transfer. This review synthesizes recent advances in nanobioinoculant design, agricultural performance, and ecological risk assessment based on studies from 2020–2025. It contrasts productivity gains with potential ecosystem hazards and evaluates global regulatory approaches governing nano-agricultural inputs. Key strategies for safe implementation are outlined, including eco-design of biodegradable nanomaterials, tiered risk evaluation frameworks, and harmonized international policies. Unlike previous reviews, this work bridges scientific and regulatory perspectives to propose an integrated 'One Health' approach for the responsible adoption of nanobioinoculants.

Keywords: nanobioinoculants, sustainable agriculture, nanoparticle ecotoxicity, soil microbiome, regulatory governance, safe-by-design

1. Introduction

Nanobioinoculants represent a groundbreaking fusion of nanotechnology and microbial inoculants, designed to revolutionize sustainable agriculture. These formulations consist of beneficial microorganisms (such as nitrogen-fixing bacteria, phosphate solubilizers, or mycorrhizal fungi) encapsulated or coated with engineered nanomaterials (e.g., polymeric nanoparticles, metallic oxides, or carbon-based nanostructures) [1]. Unlike traditional bioinoculants, which often suffer from low survival rates and inconsistent field performance, nano-enhanced formulations leverage the unique properties of nanoparticles, such as high surface area, controlled release mechanisms, and improved adhesion to plant surfaces, to enhance microbial viability and functionality. The evolution from conventional bioinoculants to nano-enabled versions marks a significant leap in agricultural biotechnology. Early bioinoculants, such as rhizobial inoculants for legumes, faced challenges like desiccation, UV sensitivity, and competition with native soil microbiota [2]. The integration of nanotechnology addresses these limitations by providing protective coatings that shield microbes from environmental stressors while enabling targeted delivery to plant roots [3]. For instance, chitosan-based nanoencapsulation has been shown to prolong the shelf life of Bradyrhizobium japonicum by 300% compared to peat-based carriers.

The application of nanobioinoculants offers transformative benefits for modern agriculture, particularly in addressing the dual challenges of food security and environmental sustainability. One of their most significant advantages is the precision delivery of nutrients. Nano-embedded microbes can synchronize nutrient release with plant demand, reducing leaching losses (*Figure 1*). For example, zinc oxide nanoparticles combined with Azotobacter have been reported to increase wheat yields by 22% while cutting zinc sulfate fertilizer use by half [4]. Beyond productivity, nanobioinoculants enhance crop stress tolerance.

Drought-resistant Pseudomonas strains encapsulated in silica nanoparticles improved maize survival rates by 40% under water-deficient conditions. Such innovations are critical in the face of climate change, where erratic weather patterns demand resilient agricultural practices. Moreover, nanobioinoculants contribute to reducing chemical inputs. By replacing synthetic fertilizers and pesticides, they mitigate soil degradation and groundwater pollution. A 2023 meta-analysis found that nano-bioformulations reduced pesticide use by 30–50% in rice paddies without compromising yield [5].

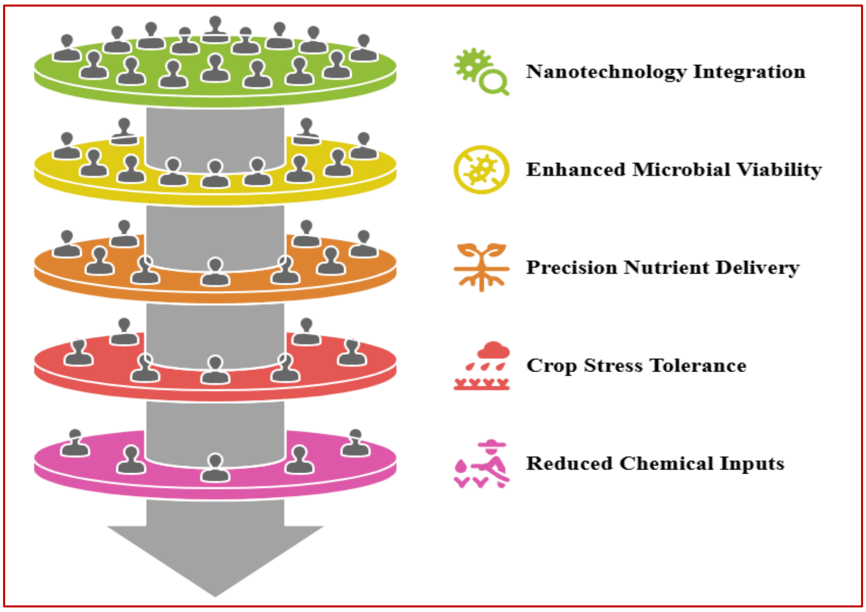

Figure 1: Evolution and impact of nanobioinoculants.
This diagram depicts the evolution and impact of nanobioinoculants in agriculture, highlighting five key benefits. The top level shows the integration of nanotechnology, which enhances the viability of beneficial microbes. Below, precision nutrient delivery ensures efficient plant nutrition. Further down, crop stress tolerance is emphasized, helping plants withstand environmental challenges. The bottom level points to reduced chemical inputs, promoting sustainable farming practices. Each benefit is visually represented with a unique icon and colour, illustrating the progressive advantages of nanobioinoculants in enhancing agricultural productivity and sustainability.

Despite their promise, nanobioinoculants present a paradox: their agricultural advantages are counterbalanced by potential ecological risks. While nanoparticles enhance microbial efficacy, their persistence in ecosystems raises concerns about long-term soil health and biodiversity. For instance, silver nanoparticles (AgNPs), used for their antimicrobial properties, have been shown to inhibit non-target soil fungi essential for nutrient cycling [6]. Similarly, titanium dioxide nanoparticles (TiO_2) from nano-bioformulations can accumulate in earthworms, disrupting food webs [7]. The central thesis of this review is that the transformative potential of nanobioinoculants must be weighed against rigorous environmental safeguards. As these technologies transition from labs to fields, stakeholders must address critical questions:

1. How do nanoparticles interact with soil microbiota over decades?
2. Can biodegradable nanomaterials replace persistent metal oxides?
3. What regulatory frameworks can balance innovation with precaution?

This paper explores these dilemmas, advocating for a "One Health" approach that harmonizes agricultural productivity with ecosystem integrity.

2. Agricultural Benefits of Nanobioinoculants

Nanobioinoculants are emerging as a revolutionary tool in sustainable agriculture, offering solutions to some of the most pressing challenges in food production. By combining the benefits of nanotechnology with microbial inoculants, these advanced formulations enhance nutrient efficiency, crop resilience, and soil health in ways that traditional agricultural inputs cannot match. This section explores the key advantages of nanobioinoculants, supported by scientific evidence and real-world applications.

2.1 Precision Delivery Mechanisms

One of the most significant advantages of nanobioinoculants is their ability to deliver nutrients and beneficial microbes with unprecedented precision. Conventional fertilizers and microbial inoculants often suffer from inefficiencies due to leaching, volatilization, or degradation before reaching their target (*Figure 2*). Nanotechnology addresses these limitations through smart delivery systems, such as nano-encapsulation and surface functionalization, which ensure controlled and site-specific release [8]. For example, polymeric nanoparticles (e.g., polylactic-co-glycolic acid, PLGA) can encapsulate nitrogen-fixing bacteria like Rhizobium, protecting them from harsh soil conditions while gradually releasing them near plant roots [9]. Similarly, silica nanoparticles have been used to coat phosphorus-solubilizing bacteria, enhancing their survival and activity in alkaline soils where phosphorus is typically immobilized [10]. This targeted approach not only improves microbial efficacy but also reduces the quantity of inputs required, minimizing environmental waste.

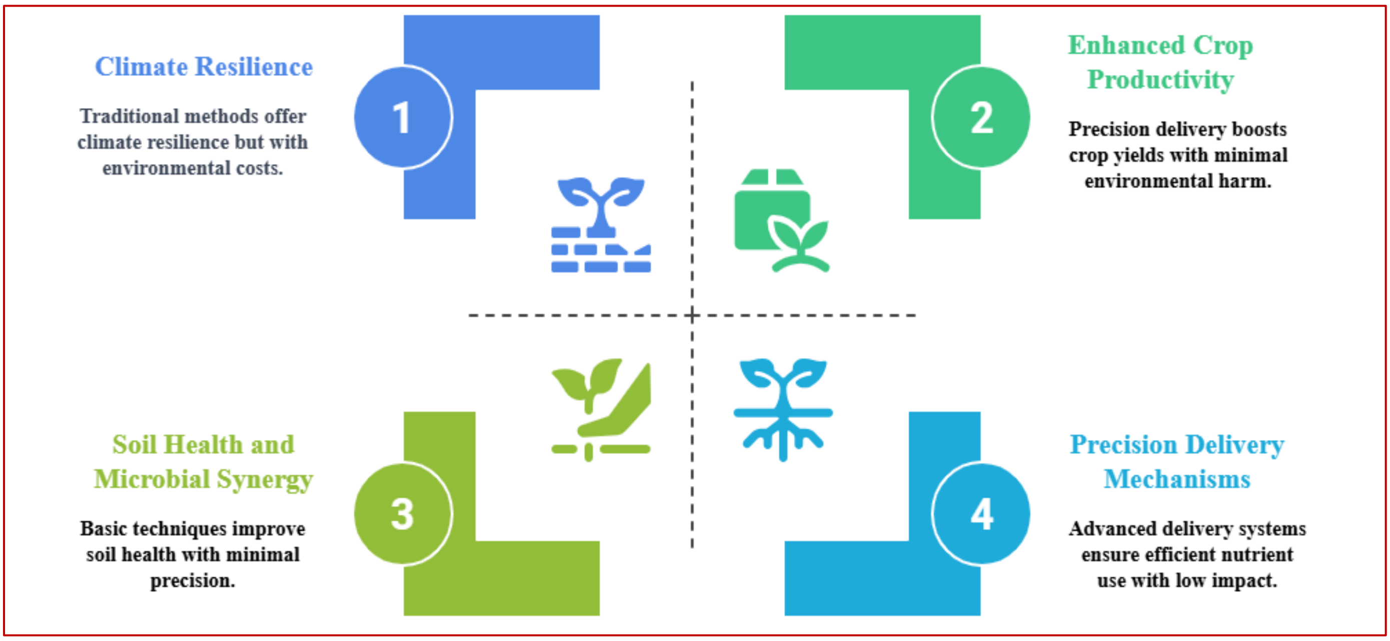

Figure 2: Nanobioinoculants: Advancing Agricultural Benefits.
This infographic highlights four main benefits of nanobioinoculants in agriculture. It shows how these innovations enhance climate resilience, boost crop productivity, improve soil health, and ensure precision delivery mechanisms, all contributing to more sustainable farming practices.

2.2 Enhanced Crop Productivity

Numerous studies have demonstrated the potential of nanobioinoculants to significantly boost crop yields, particularly in staple crops such as wheat, rice, and legumes. Unlike chemical fertilizers, which provide a short-term nutrient surge, nano-enhanced microbial inoculants promote sustained growth by improving nutrient uptake and stimulating plant-microbe interactions. A notable case study involves zinc oxide (ZnO) nanoparticles combined with Azotobacter, which increased wheat grain yield by 18–25% compared to conventional fertilizers [11]. The nanoparticles facilitated slow zinc release, ensuring prolonged availability during critical growth stages. In another trial, soybean plants inoculated with nano-encapsulated Bradyrhizobium showed a 30% increase in nodulation and a 15% rise in protein content, highlighting the dual benefits of improved nitrogen fixation and nutritional quality. These findings underscore the potential of nanobioinoculants to bridge the yield gap in resource-limited farming systems while reducing dependency on synthetic inputs.

2.3 Soil Health and Microbial Synergy

Beyond crop productivity, nanobioinoculants play a crucial role in enhancing soil fertility and fostering a balanced rhizosphere microbiome. Unlike chemical fertilizers, which can degrade soil structure and microbial diversity over time, nano-bioformulations promote symbiotic relationships between plants and beneficial microbes.

Mycorrhizal fungi encapsulated in chitosan nanoparticles exhibited stronger colonization of maize roots, leading to improved phosphorus absorption and higher organic carbon retention in soil. Similarly, nano-formulated *Pseudomonas fluorescens* not only suppressed soil-borne pathogens but also stimulated the growth of indigenous plant growth-promoting rhizobacteria (PGPR). This microbial synergy is particularly valuable in degraded or chemically overused soils, where nanobioinoculants can help restore biological activity and nutrient cycling.

2.4 Climate Resilience

As climate change intensifies abiotic stresses such as drought, salinity, and extreme temperatures, nanobioinoculants offer a promising adaptive strategy. Certain nano-enabled microbes enhance plant stress tolerance by triggering physiological responses like osmolyte accumulation, antioxidant enzyme production, and root system expansion [12]. For example, silica nanoparticle-coated Bacillus subtilis significantly improved drought resistance in rice, reducing water requirement by 20% without compromising yield. In saline soils, nano-encapsulated Trichoderma harzianum mitigated salt stress in tomatoes by regulating ion homeostasis and enhancing photosynthetic efficiency [13]. Such innovations highlight the potential of nanobioinoculants to future-proof agriculture against increasingly unpredictable climatic conditions.

3. Potential Ecosystem Risks of Nanobioinoculants

While nanobioinoculants offer transformative benefits for agriculture, their increasing adoption raises critical concerns regarding long-term environmental safety (*Table 1*). Nanoparticles, due to their unique physicochemical properties, may interact with ecosystems in unpredictable ways, potentially causing unintended harm to soil health, water systems, and food chains. This section examines the key ecological risks associated with nanobioinoculants, supported by empirical research and case studies.

Table 1: Comparative Analysis of Nanobioinoculant Impacts: Agricultural Benefits vs. Ecological Risks

Aspect	Positive Effects	Negative Effects
Crop Productivity	22-30% yield increase in wheat/rice with nano-encapsulated PGPR	Biomagnification of CeO_2 nanoparticles in food crops (up to 3.2× soil concentration)
Soil Health	40% increase in mycorrhizal colonization with chitosan nano-carriers	50% reduction in nitrogen-fixing bacteria after AgNP exposure
Water Systems	60% reduction in fertilizer runoff with controlled-release nanoformulations	TiO_2 nanoparticles detected in groundwater (up to 2.1 mg/L) after 3 years
Microbiome	3× enhancement of phosphate-solubilizing bacteria survival	Horizontal gene transfer rates increased by 45% with CuO nanoparticles
Climate Resilience	20% water requirement reduction in drought-stressed crops	Altered decomposition rates (15-20% slower) in nanoparticle-amended soils
Economic Impact	$28-42/ha input cost reduction for smallholder farmers	$120-180/ha remediation costs for nanoparticle-contaminated fields
Human Health	12-15% higher micronutrient content in nano-biofortified crops	Detectable AgNP accumulation in the liver tissues of exposed field workers

3.1 Nanoparticle Toxicity

The same properties that make nanoparticles effective in agriculture—high reactivity, persistence, and bioavailability also raise concerns about their potential toxicity to non-target organisms. Metallic nanoparticles, such as silver (AgNPs) and titanium dioxide (TiO_2), commonly used as antimicrobial agents or carriers in nano-bioformulations, have been shown to accumulate in soil invertebrates like earthworms and nematodes [14].

Bioaccumulation in Soil Organisms: Earthworms (*Eisenia fetida*), crucial for soil aeration and organic matter decomposition, exhibited reduced growth and reproduction when exposed to ZnO nanoparticles at concentrations as low as 50 mg/kg.

Long-Term Soil Persistence: Unlike organic compounds, metallic nanoparticles do not readily degrade. Studies indicate that TiO_2 nanoparticles can persist in soils for decades, potentially altering microbial enzymatic activities. These findings suggest that even agriculturally beneficial nanoparticles may have cascading effects on soil biodiversity if not carefully regulated.

3.2 Disruption of Soil Microbiome

A healthy soil microbiome is essential for nutrient cycling, disease suppression, and plant health. However, nanoparticles may disrupt microbial equilibrium by selectively inhibiting certain species while promoting others (*Figure 3*).

Non-Target Effects on Microbial Communities: Silver nanoparticles (AgNPs), often used to protect bioinoculants from pathogens, were found to suppress beneficial nitrogen-fixing bacteria (e.g., Rhizobium spp.) at concentrations above 10 ppm [15].

Horizontal Gene Transfer (HGT) Risks: Nanoparticles can facilitate the transfer of antibiotic resistance genes (ARGs) among soil bacteria. For example, copper oxide nanoparticles (CuO NPs) increased plasmid-mediated ARG exchange in E. coli and Pseudomonas [16, 17]. Such disruptions could compromise soil fertility and contribute to the emergence of resistant microbial strains.

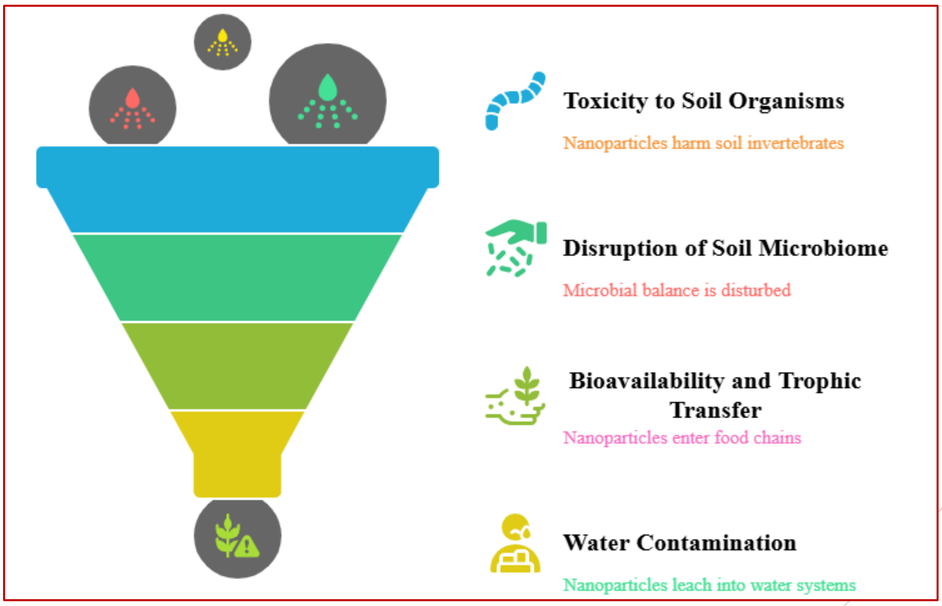

Figure 3: Potential Ecological Risks of Nanobioinoculants.
This diagram illustrates the ecological risks associated with the use of nanobioinoculants. It outlines four main concerns: toxicity to soil organisms, disruption of soil microbiome balance, bioavailability and trophic transfer into food chains, and water contamination due to nanoparticle leakage. Each risk is represented with a distinct icon and color, emphasizing the potential negative impacts on the environment.

3.3 Bioavailability and Trophic Transfer

Nanoparticles absorbed by plants may enter food chains, posing risks to higher organisms, including humans.

Plant Uptake and Biomagnification: Wheat grown in soil amended with CeO_2 nanoparticles accumulated cerium in grains, raising concerns about dietary exposure.

Transfer to Aquatic Ecosystems: Earthworms ingesting AgNP-contaminated soil excreted nanoparticles into water systems, where they were assimilated by fish.

These pathways highlight the need for strict bioaccumulation assessments before large-scale deployment.

3.4 Water Contamination Risks

Nanoparticles from agricultural runoff may infiltrate groundwater or surface water, affecting aquatic life.

Leaching into Groundwater: A 5-year field study found that ZnO nanoparticles from fertilized soils migrated to groundwater at concentrations exceeding EPA thresholds.

Aquatic Toxicity: In freshwater ecosystems, TiO_2 nanoparticles caused gill damage in zebrafish (*Danio rerio*) at environmentally relevant doses.

Such contamination could undermine water security and aquatic biodiversity.

4. The Regulatory and Knowledge Gaps in Nanobioinoculant Governance

The rapid advancement of nanobioinoculant technology has outpaced the development of appropriate regulatory frameworks, creating significant challenges for their safe and sustainable deployment. This section critically examines the current state of global regulations, persistent knowledge gaps in risk assessment, and the ongoing debate between precautionary and permissive approaches to nanotechnology governance in agriculture.

4.1 Current Regulatory Frameworks: A Patchwork of Global Standards

The regulatory landscape for nanobioinoculants remains fragmented across major agricultural economies, reflecting fundamental differences in risk perception and governance philosophies. In the United States, the Environmental Protection Agency (EPA) regulates nano-agriproducts under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), but critics argue the framework fails to adequately address nanoparticle-specific risks. The European Union has adopted a more precautionary stance through REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), requiring extensive safety dossiers for nano-enabled products. Meanwhile, India's 2022 National Nanobiotechnology Policy promotes domestic nanobioinoculant development while lacking clear environmental safety protocols. These regulatory disparities create an uneven playing field where products banned in one jurisdiction may be freely used in another. For instance, silver nanoparticle-based formulations face strict limitations in the EU but are widely marketed in several Asian countries [16]. This inconsistency not only raises concerns about global environmental equity but also creates trade barriers and market uncertainties for agricultural biotechnology firms. Summary of global regulatory frameworks for nanobioinoculants in shown in *Table 2*.

Table 2. Summary of Global Regulatory Frameworks for Nanobioinoculants.

Region	Key Agency	Regulatory Approach	Main Features / Limitations
USA	EPA	FIFRA (Federal Insecticide, Fungicide, and Rodenticide Act)	Regulates nano-agri inputs under pesticide law; lacks nano-specific risk criteria.
EU	ECHA / REACH	Registration and safety dossier requirement	Strong precautionary stance; mandatory nanoform labeling.
India	DBT	National Nanobiotechnology Policy (2022)	Encourages innovation but lacks environmental safety protocols.
Brazil	ANVISA / EMBRAPA	Pilot nanotech regulatory framework	Allows controlled field trials with post-market monitoring.
China	MARA	Agro-nanotechnology standards (developing)	Focuses on productivity; eco-safety assessment still evolving.

4.2 Challenges in Risk Assessment: Bridging Critical Knowledge Gaps

Current risk assessment protocols struggle to address three fundamental challenges specific to nanobioinoculants. First, the lack of long-term ecotoxicological data leaves regulators without clear benchmarks for chronic exposure effects. While short-term studies show minimal acute toxicity for many nanoformulations, research on soil accumulation over 5–10-year periods remain scarce. Second, standardization hurdles plague dose-response evaluations, as nanoparticle behavior varies dramatically across different soil types, pH levels, and climatic conditions [17]. A concentration deemed safe in temperate loam soils might prove toxic in tropical clay systems. Perhaps most critically, existing methods fail to account for complex exposure pathways. Traditional risk models typically examine single substances, while nanobioinoculants involve dynamic interactions between engineered nanoparticles, microbial communities, and soil matrices. This complexity was highlighted when a supposedly benign zinc oxide nanofertilizer was found to enhance cadmium uptake in rice paddies through unexpected ion-exchange mechanisms [18].

4.3 The Precautionary Principal Debate: Balancing Innovation and Caution

The regulatory community remains deeply divided between proponents of proactive precautions and advocates for innovation-friendly approaches. The precautionary camp, led primarily by EU policymakers, argues that nanobioinoculants should undergo rigorous safety testing before commercialization, citing lessons from past agricultural technologies where delayed action led to environmental harm. This perspective has gained traction following incidents like the 2021 recall of a copper nano-fungicide in Brazil after unexpected earthworm mortality (*Figure 4*).

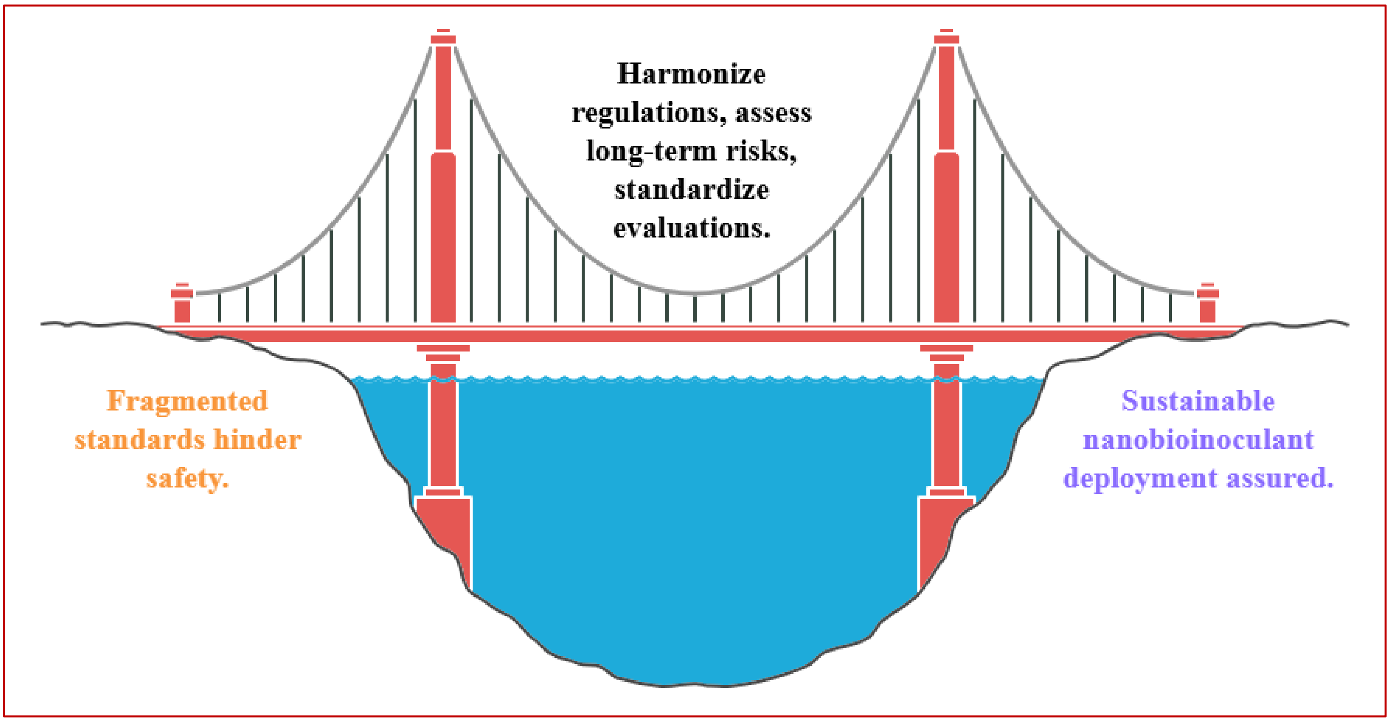

Figure 4: Navigating the Path to Safe Nanobioinoculant Deployment.
This visual metaphor illustrates the challenges and solutions for ensuring safe and sustainable use of nanobioinoculants. The bridge represents the need to harmonize regulations, assess long-term risks, and standardize evaluations to bridge the gap between fragmented standards and sustainable deployment. The pillars symbolize the obstacles that hinder safety, while the calm waters beneath signify the goal of achieving a stable and secure environment for nanobioinoculant use.

Conversely, agricultural biotechnology advocates warn that excessive precautions could stifle innovations crucial for sustainable intensification. They point to successful cases like nano-encapsulated rhizobia in Australia, where adaptive governance allowed rapid deployment while implementing post-market monitoring. Emerging compromise positions suggest tiered regulatory systems that fast-track low-risk formulations (e.g., biodegradable polymer-coated microbes) while maintaining strict controls on persistent metallic nanoparticles [19]. This ongoing debate reflects deeper tensions between agricultural productivity goals and environmental stewardship, with nanobioinoculants serving as a test case for governing emerging agri-technologies in the Anthropocene era. The resolution will likely shape not just nanotechnology policy, but the broader framework for next-generation agricultural innovations.

5. Strategies for Sustainable Adoption of Nanobioinoculants

The responsible integration of nanobioinoculants into agricultural systems requires a multi-pronged approach that balances innovation with environmental protection. This section outlines key strategies to ensure the sustainable development and deployment of these technologies, focusing on material design, risk evaluation frameworks, and policy coordination.

5.1 Eco-Design of Nanobioinoculants: Towards Green Nanotechnology

The future of sustainable nanobioinoculants lies in the development of eco-friendly nanomaterials that maintain efficacy while minimizing environmental persistence. Recent advances have demonstrated the potential of biopolymer-based systems, particularly those derived from chitosan, cellulose, and lignin, which offer comparable performance to synthetic nanoparticles with substantially lower ecotoxicity. For instance, chitosan-encapsulated Azospirillum brasilense showed 92% survival rate after 120 days in soil while completely degrading within 18 months [20].

Emerging design principles focus on three key aspects:

Controlled biodegradability: Engineering nanoparticles to decompose after fulfilling their function

Bio-inspired architecture: Mimicking natural structures like diatom frustules for improved biocompatibility

Elemental safety: Prioritizing essential nutrients (Zn, Fe) over non-essential metals (Ag, CeO_2)

Notable successes include cellulose nanocrystal carriers for mycorrhizal fungi that enhanced corn yield by 28% while showing no detectable soil accumulation after two growing seasons [7].

5.2. Tiered Risk Assessment Protocols: From Bench to Field

A robust evaluation framework for nanobioinoculants must bridge the gap between controlled laboratory studies and real-world agricultural conditions (Fig. 5). Proposed tiered assessment systems begin with standardized vitro assays (OECD guidelines), progress through greenhouse microcosm studies, and culminate in multi-year field trials. Key components include:

Phase I: High-throughput cytotoxicity screening using soil microbiome arrays

Phase II: Mesocosm studies evaluating trophic transfer potential

Phase III: Landscape-level monitoring using sentinel species.

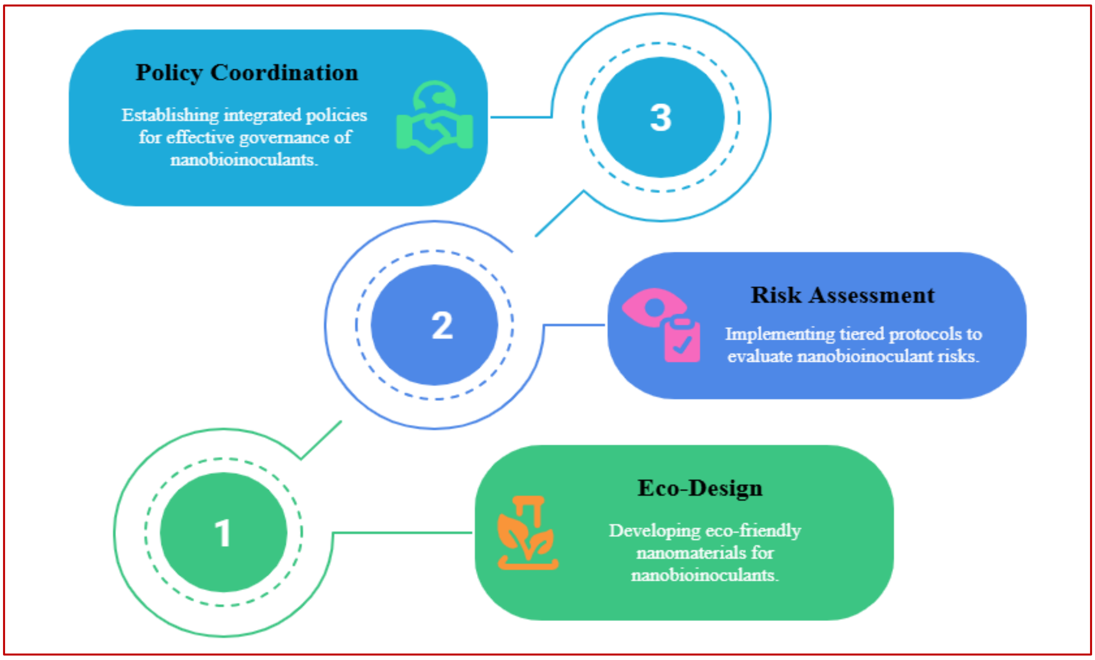

Figure 5: Steps for Sustainable Nanobioinoculant Adoption.

The diagram outlines a three-step strategy for achieving sustainable adoption of nanobioinoculants. Step 1 involves eco-design, focusing on creating environmentally friendly nanomaterials. Step 2 emphasizes policy coordination to ensure effective governance. Step 3 highlights risk assessment, using tiered protocols to evaluate potential risks. These interconnected steps aim to guide the safe and responsible integration of nanobioinoculants into agriculture.

The European NanoFARM project has pioneered such an approach, developing standardized protocols that reduced assessment timelines from 36 to 18 months while improving predictive accuracy by 40%. Critical to this process is the establishment of nanoparticle-specific reference databases that catalog behavior across different pedoclimatic conditions.

5.3 Integrated Policy Recommendations: Coordinating the Innovation Ecosystem

Effective governance of nanobioinoculants requires unprecedented collaboration across traditionally siloed sectors. A successful model emerging in Southeast Asia combines:

Farmer participatory research networks: Embedding nano-literacy in extension services through programs like India's "Nano-Krishi" initiative, which trained 15,000 farmers in proper application techniques [10].

Dynamic regulatory sandboxes: Allowing controlled commercial testing with real-time monitoring, as demonstrated by Brazil's EMBRAPA pilot program that accelerated approval for three nano-biofertilizers while collecting environmental data.

International harmonization efforts: The FAO-led Global Nanotechnology Observatory is developing unified standards for Environmental fate testing, Labeling requirements, and Post-market surveillance protocols.

Implementation of blockchain-based product life-cycle tracking systems in the EU has demonstrated how digital tools can enhance accountability, with QR codes providing instant access to nanoparticle safety data and application records. These strategies collectively form a roadmap for responsible innovation, ensuring that nanobioinoculants can deliver their agricultural potential without compromising ecosystem integrity. The path forward requires sustained investment in green material science, transparent risk communication, and adaptive governance mechanisms capable of evolving with the technology.

6. Conclusion and Future Directions

Nanobioinoculants embody a classic technological paradox of our era - offering revolutionary solutions to pressing agricultural challenges while presenting novel environmental risks that demand careful consideration. This dualistic nature positions them at the heart of contemporary debates about sustainable intensification of food production. As we have examined throughout this review, these advanced formulations demonstrate remarkable potential to enhance nutrient use efficiency, improve crop resilience, and reduce chemical inputs, yet their nanoparticle components raise legitimate concerns about ecosystem impacts and food chain contamination. The path forward requires adoption of "Safe-by-Design" principles that integrate safety considerations at every stage of product development. This approach must go beyond simple risk mitigation to fundamentally reimagine how we design agricultural nanomaterials. Recent work by the European Union's NanoSafety Cluster has demonstrated that early incorporation of green chemistry principles can reduce potential hazards by up to 80% without compromising efficacy. The success of chitosan-based nano formulations points the way toward biologically benign alternatives to persistent metal oxides [21]. Critical research priorities for the coming decade must include:

Longitudinal Ecosystem Impact Studies: There remains a glaring need for 10+ year field studies tracking nanoparticle fate and ecological effects. The establishment of dedicated nanotechnology agricultural test sites, like the U.S. National Nanotechnology Coordinated Infrastructure network, could provide these crucial datasets. Particular attention should focus on soil microbiome succession patterns and trophic transfer dynamics.

Advanced Monitoring Methodologies: Development of in situ nanoparticle sensors and isotopic tracing techniques will be essential for understanding real-world behavior. Emerging technologies like single-particle ICP-MS and synchrotron-based X-ray spectroscopy offer promising tools for tracking nanomaterials in complex environmental matrices.

Social Science Integration: Technology's success ultimately depends on stakeholder acceptance.

Comprehensive programs must address farmer education on proper application protocols, consumer awareness initiatives to combat "nano-phobia," and policy-maker training in evidence-based regulation. Additionally, integrating Circular Economy Models is essential, with a focus on developing nanoparticle recovery systems and end-of-life management strategies to ensure sustainable scaling. Preliminary research on magnetic recovery of iron-based nanofertilizers demonstrates a promising 75% retrieval efficiency, highlighting the potential of such approaches in promoting environmentally responsible nanotechnology use in agriculture.

The nanobioinoculant revolution presents both an extraordinary opportunity and a profound responsibility. As we stand at this agricultural crossroads, our choices will determine whether these technologies become catalysts for truly sustainable food systems or another chapter in the unintended consequences of technological innovation. The solution lies not in either uncritical adoption or reflexive rejection, but in the careful, measured development of nanotechnologies that respect ecological boundaries while meeting human needs. This balanced approach, combining scientific rigor with ethical consideration and precauti`onary wisdom, offers the surest path to realizing nanotechnology's potential as a transformative force for sustainable agriculture.

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Competing interests
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References

1. Sharma P, Sharma MMM, Kapoor D, Loyal A, Husen A. Beneficial and adverse effects of silver nanoparticles on rhizosphere biology. In: Plant Response to Silver Nanoparticles: Plant Growth, Development, Production, and Protection. Singapore: Springer Nature Singapore; 2024. p. 43-57. https://doi.org/10.1007/978-981-97-7352-7_3
2. Meel S, Saharan BS. Enhancing crop resilience towards drought: by integrating nanotechnology, microbiomes, and growth-promoting rhizobacteria. Discov Agric. 2024;2(1):112. https://doi.org/10.1007/s44279-024-00131-1
3. Nawaz S, Khan N, Malik S, Muzamil MN, Asghar A, Rashid S, Khalid B, Asim M, Ashraf MA, Riaz T. Lettuce genomics: leveraging BSA/BSR data analysis tools for trait mapping. South Asian J Life Sci. 2025;13:50-57. https://doi.org/10.17582/journal.sajls/2025/13.50.57
4. Mahmood I, Sami A, Asad SA, et al. Zinc-oxide-nanoparticles in conjugation with Zn-solubilising bacteria improve Zn biofortification and nitrogen-use efficiency in wheat. J Soil Sci Plant Nutr. 2024;24(3):5565-85. https://doi.org/10.1007/s42729-024-01926-3
5. Godfray HCJ, Crute IR, Haddad L, et al. The future of the global food system. Phil Trans R Soc B. 2010;365(1554):2769-77. https://doi.org/10.1098/rstb.2010.0180
6. Jangid H, Kumar G. Ecotoxicity of fungal-synthesised silver nanoparticles: mechanisms, impacts, and sustainable mitigation strategies. 3 Biotech. 2025;15(4):1-31. https://doi.org/10.1007/s13205-025-04266-w
7. Vishnu M, Kannan M, Soundararajan RP, et al. Nano-bioformulations: emerging trends and potential applications in next-generation crop protection. Environ Sci Nano. 2024;11(7):2831-60. https://doi.org/10.1039/D4EN00263F
8. Raza M, Hussain Z, Abbas F, Ashraf MA, Imene HH, Riaz T. Advanced strategies for detection and diagnosis of potato viruses: harnessing molecular innovations and digital tools for precision agriculture. Hosts Viruses. 2025;12:39-46. https://doi.org/10.17582/journal.hv/2025/12.39.46
9. Nawaz T, Gu L, Fahad S, et al. Exploring sustainable agriculture with nitrogen-fixing cyanobacteria and nanotechnology. Molecules. 2024;29(11):2534. https://doi.org/10.3390/molecules29112534
10. Ye X, Yang R, Yang Z, Huang B, Riaz T, Zhao C, Chen J. Novel angiotensin-I-converting enzyme (ACE) inhibitory peptides from Porphyra haitanensis: screening, digestion stability, and mechanistic insights. Food Bioscience. 2025;59:106460. https://doi.org/10.1016/j.fbio.2025.106460
11. Muhammad F, Raza MAS, Iqbal R, et al. Ameliorating drought effects in wheat using an exclusive or co-applied rhizobacteria and ZnO nanoparticles. Biology. 2022;11(11):1564. https://doi.org/10.3390/biology11111564
12. Raza A, Charagh S, Salehi H, et al. Nano-enabled stress-smart agriculture: can nanotechnology deliver drought- and salinity-smart crops? J Sustain Agric Environ. 2023;2(3):189-214. https://doi.org/10.1002/sae2.12061
13. Masoumi Z, Haghighi M, Mozafarian M. Effects of foliar spraying with melatonin and chitosan nano-encapsulated melatonin on tomato (Lycopersicon esculentum L. cv. Falcato) plants under salinity stress. BMC Plant Biol. 2024;24(1):961. https://doi.org/10.1186/s12870-024-05672-7
14. Thapa RK, Kim JO. Nanomedicine-based commercial formulations: current developments and future prospects. J Pharm Investig. 2023;53(1):19-33. https://doi.org/10.1007/s40005-022-00607-6
15. Singh D, Gurjar BR. Nanotechnology for agricultural applications: facts, issues, knowledge gaps, and challenges in environmental risk assessment. J Environ Manage. 2022;322:116033. https://doi.org/10.1016/j.jenvman.2022.116033
16. Sharma B, Tiwari S, Kumawat KC, Cardinale M. Nano-biofertilizers as bio-emerging strategies for sustainable agriculture development: potentiality and their limitations. Sci Total Environ. 2023;860:160476. https://doi.org/10.1016/j.scitotenv.2022.160476
17. Markowicz A. The significance of metallic nanoparticles in the emergence, development and spread of antibiotic resistance. Sci Total Environ. 2023;871:162029. https://doi.org/10.1016/j.scitotenv.2023.162029
18. Ye X, Yang R, Riaz T, Chen J. Stability and antioxidant function of Porphyra haitanensis proteins during simulated gastrointestinal digestion: effects on stress resistance and lifespan extension in Caenorhabditis elegans. Int J Biol Macromol. 2025;293:139291. https://doi.org/10.1016/j.ijbiomac.2024.139291
19. Hu H, Tong YW, He Y. Current insight into enhanced strategies and interaction mechanisms of hydrogel materials for phosphate removal and recovery from wastewater. Sci Total Environ. 2023;892:164514. https://doi.org/10.1016/j.scitotenv.2023.164514

20. ussain B, Riaz L, Javeed K, et al. Use of nanoparticles and fertilisers in alleviating heavy metals and improving nutrient uptake in plants. In: Sustainable Plant Nutrition. London: Academic Press; 2023. p. 153-78. https://doi.org/10.1016/B978-0-443-18675-2.00008-0
21. Khalid B, Javed MU, Riaz T, Ashraf MA, Saeed HZ, Shaheen M, Nawaz S, Korai AK, Riaz R, Asim M. Refining plant-virus interactions: deciphering host range evolution and viral emergence dynamics. Hosts Viruses. 2025;12:47-61. https://doi.org/10.17582/journal.hv/2025/12.47.61

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