



Biofertilizers and nano-fertilizers in modern agronomy: Potential and limitations

Dr. Bikrmaditya*

Associate Professor, Department of Agronomy, CSSS (PG) College, Machhara, Meerut, Uttar Pradesh, India

DOI: <https://doi.org/10.66856/ijaps.2026.8.1.8264>

Abstract

Rising fertilizer costs, nutrient-use inefficiency in conventional agriculture, and the environmental burden of synthetic nitrogen and phosphorus have driven sustained research interest in two distinct but often conflated technologies: biofertilizers, which use living microorganisms to enhance nutrient availability and uptake, and nano-fertilizers, which use nanoscale formulations to improve nutrient delivery efficiency. This review synthesizes peer-reviewed meta-analyses and field trials (2017-2026) evaluating both technologies' agronomic potential and documented limitations. Biofertilizers — including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), nitrogen-fixing bacteria, and phosphate solubilizers — show consistent, well-replicated yield benefits of 8-20% across climates in a 171-study global meta-analysis, with substantially larger biomass and nutrient-uptake benefits (up to 100%+) under drought stress or in mycorrhizal associations, and their efficacy is strongly moderated by soil phosphorus status, climate, and choice of microbial strain. Nano-fertilizers present a more contested evidence base: a landmark meta-analysis of 78 studies found a median 20-30% efficacy gain over conventional analogues, and numerous promotional field trials report large yield and nutrient-use-efficiency gains for nano-urea and nano-zinc formulations, yet an independent, peer-reviewed two-year field trial found nano-urea substitution for conventional nitrogen produced significant yield penalties (13-21.6%) and reduced grain protein content in rice and wheat, directly contradicting manufacturer claims. We conclude that biofertilizers represent a mature, context-dependent but scientifically well-supported technology best suited to phosphorus-limited, dry, or drought-prone systems, while nano-fertilizers remain a promising but still unsettled technology whose real-world performance, environmental safety, and appropriate use protocols require substantially more independent, field-scale verification before they can be recommended as a substitute — rather than a closely monitored supplement — to conventional fertilization.

Keywords: Biofertilizers, nano-fertilizers, plant growth-promoting rhizobacteria (PGPR)

Introduction

The Case for Fertilizer Innovation

Conventional synthetic fertilizers, while central to the yield gains of the past century, suffer from well-documented inefficiencies: global average nitrogen recovery efficiency in major cereals remains only around 30-40%, with the remainder lost to leaching, volatilization, and denitrification, carrying both economic and environmental costs including nitrate contamination of water supplies and nitrous oxide emissions. These inefficiencies, combined with volatile fertilizer prices and the finite nature of phosphate rock reserves, have motivated two distinct innovation pathways explored in this review: biological nutrient management through living microbial inoculants, and nanotechnology-enabled nutrient delivery systems.

Defining the Two Technologies

Biofertilizers are formulations containing living microorganisms — bacteria, fungi, or cyanobacteria — that, when applied to seed, soil, or plant surfaces, colonize the rhizosphere or plant tissue and enhance nutrient availability through nitrogen fixation, phosphate solubilization, or growth-promoting hormone production. Major categories include nitrogen-fixing bacteria (*Rhizobium*, *Azotobacter*, *Azospirillum*), phosphate-solubilizing bacteria and fungi, arbuscular mycorrhizal fungi (AMF), and the broader category of plant growth-promoting rhizobacteria (PGPR), which may act through multiple mechanisms

simultaneously. Nano-fertilizers, by contrast, are non-living formulations in which nutrients are either encapsulated within, coated onto, or synthesized as nanoscale (1-100 nm) particles, with the goal of improving nutrient solubility, enabling controlled or targeted release, and increasing the surface-area-to-volume ratio available for plant uptake. Despite their mechanistic differences, both technologies are marketed on similar claims — higher nutrient-use efficiency, reduced chemical fertilizer requirements, and improved yield — making a side-by-side evidentiary comparison useful for practitioners evaluating which, if either, merits investment in a given cropping system.

Scope of This Review

This review draws on global meta-analyses, systematic reviews, and independent field trials to characterize the documented agronomic potential and limitations of both technologies, with particular attention to the gap between promotional claims and independently verified, peer-reviewed field performance — a gap that emerges as a central and recurring theme in the nano-fertilizer literature specifically.

Biofertilizers: Mechanisms and Categories

1. Nitrogen-Fixing Bacteria

Symbiotic (*Rhizobium*-legume) and free-living or associative (*Azotobacter*, *Azospirillum*) nitrogen-fixing bacteria convert atmospheric N₂ into plant-available

ammonium, historically the best-established and most widely commercialized biofertilizer category, particularly for legume crops where rhizobial inoculation is routine agricultural practice in many regions.

2. Phosphate-Solubilizing Microorganisms

Phosphate-solubilizing bacteria and fungi release organic acids and enzymes (notably phosphatases) that convert soil-bound, plant-unavailable phosphorus into soluble forms, addressing one of the most widespread nutrient constraints in acidic and calcareous soils worldwide.

3. Arbuscular Mycorrhizal Fungi (AMF)

AMF form symbiotic associations with the majority of crop plant roots, extending the effective root system through extraradical hyphal networks that dramatically increase the soil volume accessible for phosphorus and, to a lesser extent, nitrogen and potassium uptake, in exchange for plant-supplied carbon.

4. Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR is a broad functional category encompassing bacteria that promote plant growth through diverse mechanisms including nitrogen fixation, phosphate solubilization, phytohormone (auxin) production, and production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, an enzyme that reduces plant ethylene levels and thereby alleviates multiple abiotic stresses including drought.

Biofertilizer Agronomic Performance

The most comprehensive evidence base for biofertilizer efficacy comes from a 171-publication global meta-analysis, which found yield responses varying systematically by climate — 20.0% in dry climates, 14.9% in tropical climates, 10.0% in oceanic climates, and 8.5% in continental climates — with the pattern attributed to biofertilizers providing the greatest marginal benefit where abiotic stress or nutrient limitation is most severe. The same

analysis found biofertilizer efficacy increased with soil phosphorus availability in the order AMF, phosphate solubilizers, then nitrogen fixers, and that biofertilizers improved phosphorus-use efficiency by 7.5 kg of yield per kg of phosphorus applied (up to 7.8 kg in legumes) and nitrogen-use efficiency by 5.8 kg of yield per kg of nitrogen applied. A maize-specific meta-analysis found biofertilizers increased field yield by 15.3% and greenhouse yield (using field soil) by 18.4%, with strains producing ACC deaminase outperforming non-producing strains (18.5% versus 11.1% yield increase) — one of the few PGPR mechanisms found to reliably predict field performance, underscoring that biofertilizer efficacy depends heavily on matching specific microbial traits to specific stress conditions rather than treating “biofertilizer” as a single undifferentiated input. AMF inoculation shows some of the largest and most consistent effect sizes in the biofertilizer literature: a 187-study meta-analysis found AMF increased plant biomass by 47%, nitrogen uptake by 67%, and phosphorus uptake by 105%, with a separate independent meta-analytical synthesis finding comparable biomass gains (29.7% total biomass) and nutrient uptake increases (36.3% phosphorus, 22.1% nitrogen, 18.5% potassium). AMF benefits are substantially amplified under drought stress: a 122-study, 3,534-observation meta-analysis found AMF inoculation under drought increased plant biomass by 220.9% and phosphorus uptake by 135.6% at favorable carbon-to-nitrogen ratios, indicating that AMF’s value proposition is strongest precisely in the water-limited conditions where crops most need nutritional support. PGPR shows a similar stress-amplification pattern: a 52-article meta-analysis found PGPR increased shoot mass by 28% and yield by 19% under well-watered conditions, rising to 45% and 40% respectively under drought stress, reinforcing that both major biofertilizer categories deliver disproportionate value in marginal, stress-prone growing environments rather than already-optimal ones. Figure 1 summarizes these effect sizes across the major independent meta-analyses reviewed.

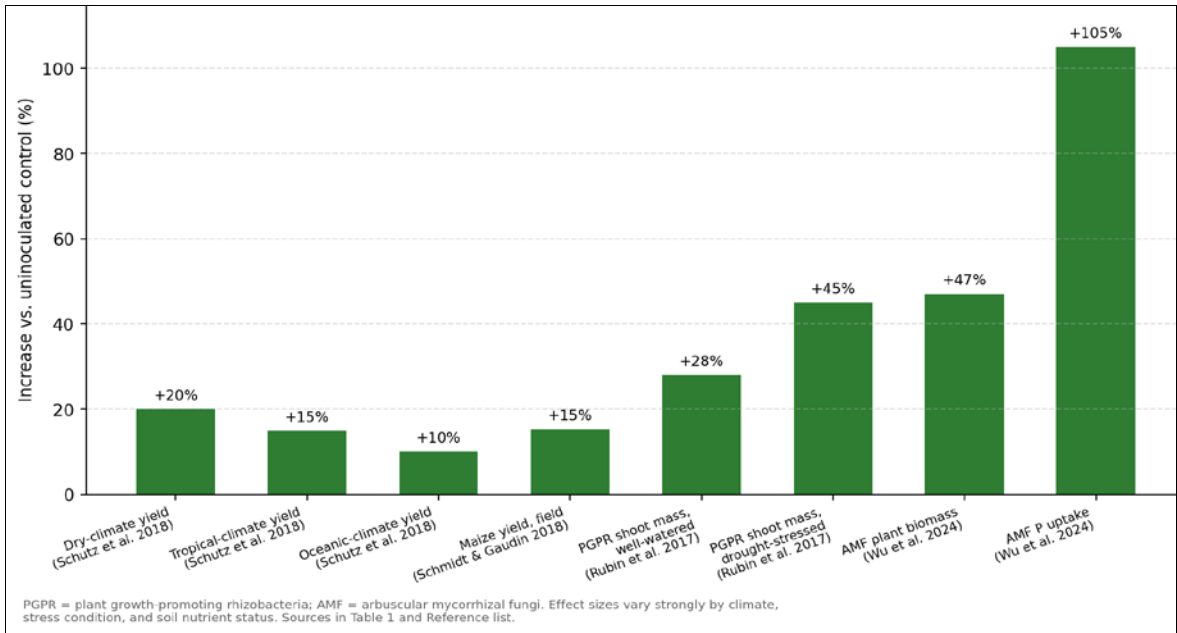


Fig 1: Biofertilizer effects on crop yield, biomass, and nutrient uptake across independent global meta-analyses

Biofertilizer Limitations

- **Strain and ecological specificity:** biofertilizer performance depends heavily on matching microbial strain to soil, climate, and crop — a maize meta-analysis found some commonly marketed genera (*Bacillus*, *Enterobacter*, *Pantoea*) did not consistently increase yields, with confidence intervals overlapping zero, while only strains with specific traits (e.g., ACC deaminase production) reliably improved outcomes.
- **Field-greenhouse performance gap:** biofertilizer effects are frequently smaller and more variable in field trials than in controlled greenhouse or growth-chamber studies, reflecting competition from native soil microbial communities, environmental variability, and inconsistent field application/survival of introduced organisms.
- **Shelf-life and viability constraints:** because biofertilizers contain living organisms, product quality depends on maintaining microbial viability through storage, transport, and field application, with viability loss under heat or prolonged storage a persistent commercial quality-control challenge.
- **Diminishing returns at high soil fertility:** biofertilizer yield response is generally small when applied to soils already well-supplied with the target nutrient, meaning biofertilizers substitute poorly for soil testing and targeted conventional fertilization on already-fertile land.
- **Native community competition:** introduced microbial inoculants must compete with, or integrate into, existing native soil microbial communities, and a maize-focused meta-analysis specifically called for biofertilizer development frameworks that account for native community ecology rather than treating inoculation as occurring in a biologically neutral soil environment.

Nano-fertilizers: Rationale and Categories

Nano-fertilizers encompass several distinct formulation strategies: nanoscale elemental or oxide particles of essential nutrients (e.g., zinc oxide, iron oxide nanoparticles), nano-encapsulated conventional fertilizers designed for controlled release, and nanocomposite carriers (nano-zeolites, nano-clays, nano-chitosan) that bind and gradually release nutrients over extended periods — in some documented cases sustaining nutrient release for over 1,000 hours compared to 200-300 hours for conventional formulations. The most commercially prominent example is nano-urea, a foliar-applied liquid nitrogen formulation marketed heavily in India by the Indian Farmers Fertiliser Cooperative (IFFCO) with claims of matching conventional urea's yield performance at a fraction of the applied nitrogen volume.

Nano-fertilizer Performance: Claims and Independent Verification

The nano-fertilizer evidence base displays a wider and more concerning gap between industry-associated promotional claims and independent, peer-reviewed verification than is seen in the biofertilizer literature. The most rigorous independent synthesis to date — a meta-analysis of 78 published studies — found nanoagrochemicals (encompassing both nanofertilizers and nanopesticides) delivered a median 20-30% efficacy gain over conventional analogues, but the same analysis explicitly flagged that most existing studies were conducted under controlled laboratory or greenhouse conditions, that comparisons with conventional products often lacked adequate quality controls, and that no comprehensive field-scale study existed evaluating both efficacy and environmental impact together — a critical evidentiary gap that remains only partially closed by more recent literature. Numerous individual field studies and industry-associated reviews report substantial gains: nano-urea applications to rice reportedly increased yield by 28.6% while cutting nitrogen input by 44%, and nano-zinc applications to wheat reportedly increased yield by 31.2% while raising grain zinc content by 41%, with nutrient-use efficiency gains commonly claimed to exceed 50%, compared with 30-50% for conventional fertilizers.

These claims stand in direct tension with an independent, peer-reviewed two-year field study conducted by researchers at Punjab Agricultural University, which tested foliar nano-urea combined with 50% of the recommended nitrogen dose against 100% conventional urea in a rice-wheat rotation. The study found nano-urea substitution significantly decreased grain yield by 13.0% in rice and 17.2% in wheat, reduced grain nitrogen content by 17% and 11.5% respectively, and reduced grain protein content by 35% and 24% respectively — alongside reduced chlorophyll content, dry matter accumulation, tiller density, and root growth. A related independent trial similarly found nano-DAP (di-ammonium phosphate) reduced wheat yield by 16.1% relative to conventional DAP. The researchers concluded that nano-urea's claimed ability to match conventional urea's yield performance requires substantially more long-term (5-7 year) field evaluation before it can be recommended as a substitute, rather than a supplement, for conventional nitrogen fertilization — a materially more cautious conclusion than the promotional literature suggests. Notably, other independent studies have found more favorable results when nano-urea is used to supplement (rather than substitute for) a high proportion of the conventional recommended dose — for example, 75% conventional nitrogen plus nano-N and nano-Zn foliar sprays achieving yields statistically equivalent to the full recommended dose across several crops — suggesting that nano-fertilizers may have a legitimate role as a nitrogen-reduction tool at modest substitution rates even where more aggressive substitution fails. Figure 2 contrasts these promotional and independently verified findings directly.

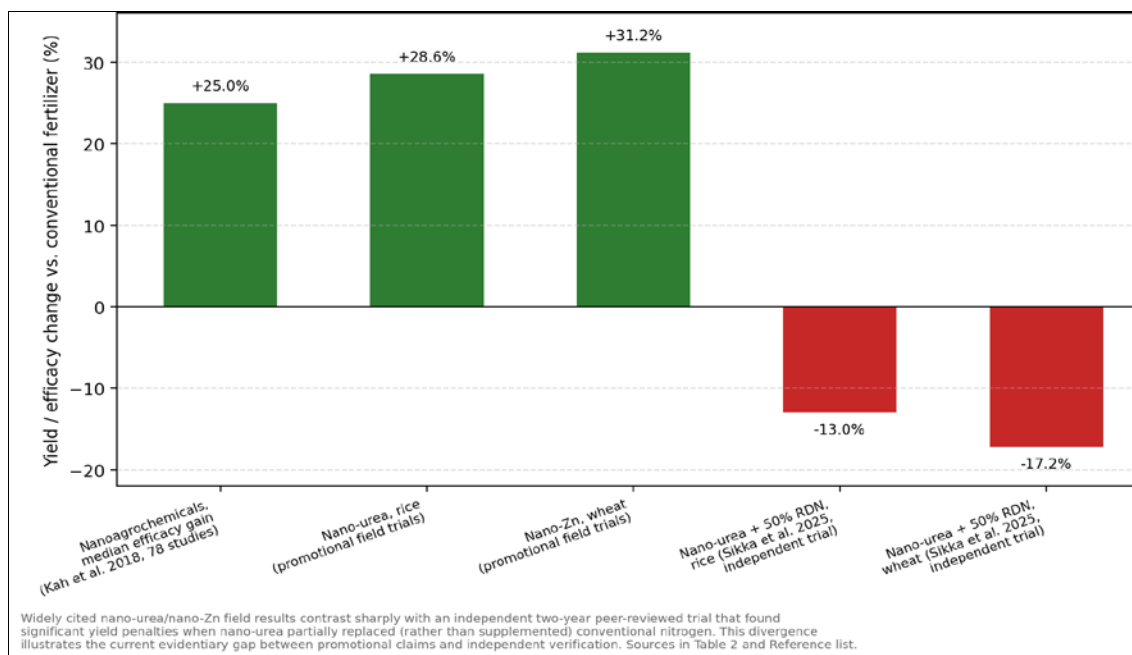


Fig 2: Nano-fertilizer performance: promotional field-trial claims vs. independent, peer-reviewed evaluation

Table 1: Representative biofertilizer effects on crop yield, biomass, and nutrient uptake from peer-reviewed meta-analyses.

Biofertilizer Type	Reported Effect	Study (Scope)	Source (DOI)
Mixed biofertilizers (overall, by climate)	Yield +20.0% (dry), +14.9% (tropical), +10.0% (oceanic), +8.5% (continental)	171 publications, global meta-analysis	10.3389/fpls.2017.02204
Biofertilizers, phosphorus use efficiency	+7.5 kg yield per kg P applied (up to +7.8 in legumes)	Global meta-analysis subgroup	10.3389/fpls.2017.02204
Biofertilizers, nitrogen use efficiency	+5.8 kg yield per kg N applied	Global meta-analysis subgroup	10.3389/fpls.2017.02204
PGPR (maize, field conditions)	+15.3% grain yield; +18.4% in greenhouse (field soil)	Meta-analysis of field/greenhouse maize trials	10.1093/femsec/fiy094
PGPR with ACC deaminase activity	+18.5% yield vs. +11.1% for non-ACC-deaminase strains	Maize meta-analysis subgroup	10.1093/femsec/fiy094
PGPR, well-watered conditions	Root mass +35%; shoot mass +28%; yield +19%	52-article meta-analysis	PGPR drought meta-analysis (see reference list)
PGPR, drought-stressed conditions	Root mass +43%; shoot mass +45%; yield +40%	52-article meta-analysis	PGPR drought meta-analysis (see reference list)
Arbuscular mycorrhizal fungi (AMF), biomass/nutrients	Biomass +47%; N uptake +67%; P uptake +105%	187-study global meta-analysis	10.1186/s12870-024-05638-9
AMF, shoot/root/total biomass (independent synthesis)	Shoot +36.3%; root +28.5%; total +29.7%	Meta-analytical review, multiple crops	10.3390/agriculture10090370
AMF, nutrient uptake (independent synthesis)	P +36.3%; N +22.1%; K +18.5%	Meta-analytical review, multiple crops	10.3390/agriculture10090370
AMF under drought stress	Biomass +220.9%; N uptake +23.7%; P uptake +135.6%	122-study, 3,534-observation meta-analysis	10.1016/j.scitotenv.2024.176874 (see reference list)
Combined PGPR + reduced chemical fertilizer (wheat)	Grain yield +28% to +37% vs. uninoculated, unfertilized control	Field trial, rainfed wheat cultivar	10.3390/agriculture12071524

Note: Effect sizes reflect inoculated/treated relative to uninoculated controls; ranges reflect climate, crop, soil-nutrient-status, and stress-condition differences. See Reference list for full citations.

Table 2: Nano-fertilizer performance claims and independent field-trial findings.

Nano-fertilizer / Claim	Reported Effect	Study Type	Source (DOI)
Nanoagrochemicals (fertilizers + pesticides), median gain	+20% to +30% efficacy vs. conventional analogues	78-study meta-analysis	10.1038/s41565-018-0131-1
Nano-urea, rice (promotional claim)	+28.6% yield with 44% less N input	Multi-location field demonstration	See reference list (industry/review sources)
Nano-zinc, wheat (promotional claim)	+31.2% yield; +41% grain Zn content	Multi-location field demonstration	See reference list (industry/review sources)
Nano-Si, maize under salinity	Biomass +110%; nutrient-use	Split-plot field experiment	10.3390/plants14050673

	efficiency +105-110%		
Nano-N + nano-Zn (75% recommended N), multi-crop	Yield statistically equivalent to 100% recommended dose	Multi-season field trial, wheat-maize / mustard-millet	10.1038/s41598-023-48951-3
Nano-urea + 50% RDN, rice (independent trial)	-13.0% yield; -17% grain N content; -35% grain protein	2-year peer-reviewed field trial	10.1007/s11104-024-07157-w
Nano-urea + 50% RDN, wheat (independent trial)	-17.2% yield; -11.5% grain N content; -24% grain protein	2-year peer-reviewed field trial	10.1007/s11104-024-07157-w
Nano-DAP, wheat (independent trial)	-16.1% yield vs. conventional DAP	Independent field evaluation	See reference list (PAU field study)

Note: Promotional/industry-associated figures are distinguished from independent, peer-reviewed field trials; both are included to illustrate the current evidentiary divergence in the literature.

Nano-fertilizer Limitations and Environmental Concerns

- **Substitution vs. supplementation confusion:** much of the negative independent evidence concerns nano-fertilizer use as a partial substitute for conventional fertilizer at reduced total nutrient rates, whereas most positive results involve nano-fertilizer as a supplement alongside a high proportion of the conventional recommended dose — a distinction frequently blurred in promotional claims.
- **Limited field-scale, long-term evidence:** the majority of favorable nano-fertilizer results derive from short-term trials (1-2 seasons) or controlled greenhouse/laboratory conditions, with researchers explicitly calling for 5-7 years of field evaluation before firm agronomic recommendations can be made.
- **Ecotoxicological uncertainty:** metal-based nanoparticles (ZnO, CuO, Fe-oxide, Ag) have documented toxicity to beneficial soil bacteria and fungi in laboratory studies, with effects on soil microbial community structure and enzyme activity that remain poorly characterized under realistic, long-term field application scenarios.
- **Dose-dependent hormesis:** several reviews note nanoparticle effects on soil microbial and enzymatic activity follow a hormetic (dose-dependent, non-monotonic) pattern, where low concentrations stimulate beneficial activity but higher concentrations become inhibitory or toxic — complicating the development of simple, universal application-rate guidance.
- **Regulatory and standardization gaps:** nano-fertilizers currently lack the standardized efficacy testing, quality control, and environmental risk-assessment frameworks applied to conventional fertilizers, making independent verification of manufacturer claims both difficult and inconsistent across products and markets.
- **Cost and accessibility:** nano-fertilizer production requires more sophisticated manufacturing than conventional fertilizer, and while per-hectare application volumes are lower, per-unit product costs are typically higher, with the net economic case for smallholder farmers still poorly established outside of subsidized distribution programs.

Comparative Assessment: Biofertilizers vs. Nano-fertilizers

Biofertilizers and nano-fertilizers differ not only mechanistically but in the maturity and consistency of their

supporting evidence base. Biofertilizer research, spanning several decades and encompassing well-powered meta-analyses across hundreds of individual field studies, has converged on a reasonably consistent picture: modest but reliable yield gains (8-20%) that scale with abiotic stress and phosphorus limitation, larger nutrient-uptake gains (up to 100%+) for AMF specifically, and clearly identified failure modes (strain mismatch, native-community competition, viability loss) that inform practical deployment guidance. Nano-fertilizer research, by contrast, remains comparatively young, geographically concentrated (with much of the most prominent commercial deployment centered on India's nano-urea program), and characterized by a wide and largely unreconciled gap between industry-associated promotional field results and independent, peer-reviewed evaluation — a gap most starkly illustrated by the contrast between claimed 28-31% yield gains and independently documented 13-21.6% yield penalties for chemically similar nano-urea and nano-DAP products. This does not mean nano-fertilizers lack genuine potential — the broader 78-study meta-analysis does document a real, if more modest, average efficacy gain, and favorable results are consistently observed when nano-fertilizers supplement (rather than substitute for) a high base rate of conventional fertilizer — but it does mean the technology's current evidence base supports considerably more cautious, conditional recommendations than much of the commercial and promotional literature suggests.

Combining Biofertilizers, Nano-fertilizers, and Conventional Inputs

A growing body of field research suggests the most agronomically robust path forward may not be choosing between conventional, biological, and nanoscale nutrient sources, but rather integrating them. Field trials combining PGPR inoculation with reduced-rate chemical fertilizer have found grain yield increases of 28-37% relative to an unfertilized, uninoculated control when PGPR was paired with 50% of the need-based nitrogen, phosphorus, and zinc chemical fertilizer dose — a combination that outperformed either the sole biofertilizer or sole chemical-fertilizer treatment, and that reduced total nitrogen and phosphorus fertilizer requirements by 16.7% and 25% respectively in a related integrated nutrient management study. Similarly, several nano-fertilizer field trials reviewed in Section 6 achieved their most favorable, statistically defensible results not by replacing conventional fertilizer outright but by pairing a substantial (e.g., 75%) conventional dose with a modest nano-fertilizer supplement, achieving yields statistically equivalent to the full recommended dose while reducing total nitrogen requirements. There is also emerging interest in combining the two alternative technologies directly: so-called “nano-biofertilizers,” in which nanoscale

carriers are used to encapsulate and protect living microbial inoculants, aim to address biofertilizers' shelf-life and field-survival limitations (Section 4) through nanoscale protective delivery, though this combined approach remains at an earlier stage of field validation than either parent technology individually. Collectively, this integration-oriented evidence suggests that the more actionable near-term question for practitioners may be “what is the optimal combination and substitution rate” rather than “which single technology performs best,” a framing better supported by the current literature than a strict either-or comparison.

Regional Adoption and Economic Considerations

Biofertilizer adoption is most institutionally advanced in regions with established agricultural extension infrastructure and long-standing rhizobial inoculant programs for legume crops, including parts of South Asia, sub-Saharan Africa, and South America, where the relatively low cost of microbial inoculants relative to imported chemical fertilizer makes the economic case comparatively straightforward, particularly for smallholder farmers facing binding fertilizer-cost constraints. Nano-fertilizer commercialization has advanced furthest in India, where IFFCO's nano-urea program has been tested and promoted across a claimed 11,000 locations and 94 crops with government and cooperative-sector backing, reflecting both genuine agronomic interest and policy-level enthusiasm for reducing a heavily subsidized conventional urea program's fiscal burden; this concentrated, policy-driven deployment context is itself part of why the gap between promotional and independent findings documented in Section 6 carries such significant practical stakes for farmers who adopt nano-urea based on marketed yield-parity claims. In both cases, the economic calculus for individual farmers depends heavily on relative pricing between conventional and alternative inputs, the reliability of local product quality control, and — for nano-fertilizers specifically — the substitution rate at which the product is actually used relative to the rate at which it has been field-validated to perform safely.

Conclusion

Biofertilizers and nano-fertilizers each offer genuine, evidence-supported potential to improve nutrient-use efficiency and reduce reliance on conventional chemical fertilizers, but they occupy different positions on the maturity-to-evidence spectrum. Biofertilizers, particularly AMF and PGPR with well-characterized functional traits, represent a scientifically mature technology best deployed in phosphorus-limited, dry, or drought-prone cropping systems, with well-understood (if not fully solved) limitations around strain specificity and field variability. Nano-fertilizers represent a genuinely promising but considerably less settled technology: real efficacy gains are documented in controlled and promotional studies, but the sharp divergence between these results and independent field verification — particularly for nano-urea used as a substitute rather than supplement for conventional nitrogen — means the technology should currently be deployed cautiously, as a monitored complement to (not wholesale replacement of) conventional fertilization, pending the longer-term, independently verified field trials that researchers on both sides of the debate agree are still needed.

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