Plant Growth-promoting Rhizobacteria from Mechanism to Market: A Critical Appraisal of Scientific Advances, Formulation Strategies and Commercialisation Constraints

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Abstract

Plant growth-promoting rhizobacteria (PGPR) occupy an unusual position in agricultural science. The mechanistic literature is extensive and increasingly precise, yet the translation of that knowledge into products that perform dependably across ordinary farming conditions remains partial. This review examines why the gap persists, treating mechanism, ecology, formulation and commercial architecture as one connected problem rather than as separate literatures. Peer-reviewed evidence retrieved through Europe PMC and Crossref Metadata Search, supplemented by targeted verification of foundational works, was appraised for design adequacy, scale of inference and consistency, with searches closing on 5 June 2026. Four findings emerge. Mechanistic demonstration has advanced faster than agronomic demonstration, and the inferential step from a characterised trait to a yield response is frequently asserted rather than tested. Meta-analytic estimates of yield benefit are positive but modest and strongly conditioned by environment, with the largest responses reported under water limitation and in phosphorus-deficient or otherwise constrained soils; this conditionality is a property of the technology, not a defect of individual trials. Formulation research has diversified into encapsulation, hydrogel and seed-coating platforms that demonstrably extend viability, yet very few studies follow a formulation through storage, sowing, colonisation and yield in the same experimental system, so the chain of evidence linking shelf-life to field benefit is largely inferred. Commercial and regulatory constraints, including inconsistent product quality, fragmented registration pathways and thin economic evidence for adoption, are frequently listed but rarely investigated with the rigour applied to mechanism. Priorities for the field are therefore reframed around multi-environment trials with genotype-by-environment analysis, mandatory strain-level verification in marketed products, standardised viability and colonisation reporting, and the design of consortia on ecological rather than additive principles. The evidence supports cautious optimism about conditional, well-targeted deployment and does not support claims of general substitutability for mineral fertilisation.

Keywords: Bioinoculant formulation; rhizosphere colonisation; microbial biostimulants; synthetic microbial communities; inoculant quality control; agricultural biologicals regulation; context-dependent efficacy.

1. Introduction

Rhizobacteria capable of improving plant growth have been studied intensively for more than four decades, and in the case of the most extensively investigated genus the research record now spans a century, having passed through successive phases of enthusiasm, disappointment and methodological reconstruction (Pelagio-Flores et al., 2025). The accumulated mechanistic account is now detailed. Bacteria colonising the root surface and adjacent soil can fix atmospheric dinitrogen, mobilise sparingly soluble phosphorus, produce siderophores that alter iron availability, synthesise or degrade plant hormones, emit volatile compounds that modify root architecture, and prime host immunity against pathogens (Glick, 2012; Vacheron et al., 2013; Vejan et al., 2016). Each of these capacities has been demonstrated repeatedly under controlled conditions, and for several the underlying genetics and biochemistry are well characterised. The scientific foundation, judged on its own terms, is sound.

The agricultural record is more equivocal. Global meta-analytic synthesis indicates that biofertilisation raises yield and nutrient uptake on average, but the mean effect is moderate and its magnitude depends heavily on soil status and climate, with the strongest responses observed in dry climates and in soils of low phosphorus availability (Schütz et al., 2018). A separate quantitative synthesis found that rhizobacterial inoculation improved plant biomass more reliably under water deficit than under well-watered conditions, again pointing to environmental limitation as the principal determinant of benefit (Rubin et al., 2017). Practitioners and reviewers alike have long noted that laboratory or glasshouse responses attenuate or disappear in the field, and the observation has become sufficiently routine that it is often reported without analysis (Backer et al., 2018; Díaz-Rodríguez et al., 2025). Recent field-scale work in maize further showed that a microbial consortium can modify rhizosphere community composition and plant stress-related responses under field conditions, while the authors also noted the need for further work to achieve consistent agricultural benefits (Francioli et al., 2025).

Three explanations for this attenuation compete in the literature, and they carry different implications. The first attributes failure to the inoculant itself: insufficient viable cells at the point of use, loss of activity during storage, or formulation chemistry poorly matched to the delivery route. This diagnosis has driven substantial work on carriers, encapsulation, hydrogels and seed treatments (Bashan et al., 2014; Khan et al., 2023). The second attributes failure to ecology: an introduced strain enters a soil already occupied by a resident community that resists invasion, and the introduced population declines below any functionally meaningful density within weeks (Klimasmith et al., 2024; Xu et al., 2025). The third attributes failure to context: the trait that the strain expresses is agronomically irrelevant in soils where the corresponding resource is not limiting, so a strain selected for phosphate solubilisation will produce no measurable benefit where phosphorus is abundant (Schütz et al., 2018; Sun et al., 2026). These explanations are not mutually exclusive, and the more interesting question is how they interact, but much of the literature treats only one at a time. A recent review of agricultural microbiome deployment similarly emphasises that invasion, persistence, community stability and delivery need to be considered together when translating

microbial candidates from simplified experiments to agroecological settings (Copeland et al., 2025).

Commercial development has proceeded in parallel with, rather than in response to, this uncertainty. Product ranges have expanded, national industries have consolidated in several large agricultural economies, and regulatory categories have been created to accommodate microbial inputs that are neither conventional fertilisers nor pesticides (Sun et al., 2025; Xavier et al., 2026). The consequences of expansion without corresponding verification have become visible. An independent assessment of commercial mycorrhizal products found limited viability of the declared organisms, contamination with plant pathogens, and in several cases a negative effect of the product microbiota on crop growth (Koziol et al., 2024). That study concerns mycorrhizal rather than bacterial products, and its findings cannot be transferred directly, but it establishes that quality failure in agricultural microbial products is a documented phenomenon rather than a theoretical risk, and comparable verification for bacterial inoculants is sparse. Methodological heterogeneity adds a further interpretive constraint: proposed standards for field testing identify low numbers of tested environments, incomplete site and management descriptions, and missing soil moisture or temperature data as recurrent deficiencies in published PGPM trials (Neuhoff et al., 2024).

Existing reviews of this field are numerous and generally competent within their chosen boundaries. Several provide thorough mechanistic accounts (Wang & Xu, 2026), others survey formulation technologies (Khan et al., 2023), and a smaller number address regulation or market structure (Mashabela et al., 2025). What is scarce is a synthesis that holds these strands together and asks how a weakness in one propagates into the others. A formulation that preserves viability perfectly cannot compensate for a strain whose principal trait is irrelevant in the target soil. A strain with excellent rhizosphere competence delivers nothing if the marketed product does not contain it in verified numbers. A regulatory pathway that does not require efficacy evidence removes the commercial incentive to generate the multi-environment data that would resolve the conditionality problem. Treating these as separate literatures has permitted each to develop internally consistent standards of evidence that do not connect.
A further difficulty concerns the evidential status of mechanism. Demonstration that a strain possesses a trait in vitro, that the trait has a genetic basis, and that inoculation is followed by improved growth in a pot experiment does not establish that the trait caused the growth response, still less that it will do so in soil. Mechanistic plausibility and demonstrated agronomic effectiveness are distinct claims requiring distinct evidence, and the distinction is frequently blurred. Recent work on genome-informed strain selection makes this problem explicit by treating functional gene content as a hypothesis to be tested rather than as a predictor of performance (Gonçalves, 2026).

1.1 Scope, Research Gap and Objectives

This review addresses free-living and associative plant growth-promoting rhizobacteria applied to crops as inoculants, together with the formulation technologies through which they are delivered and the production, quality-assurance and regulatory systems that determine whether they reach farmers in functional condition. Rhizobial symbionts of legumes are considered only where they inform general questions of inoculant survival, delivery or quality control, because their agronomic performance rests on an obligate symbiosis that does not generalise. Mycorrhizal fungi and fungal biocontrol agents are

treated similarly, as comparators rather than as subjects. Genetically modified organisms are discussed only in relation to regulatory architecture.

The gap this review addresses is the absence of an integrated critical account linking mechanistic knowledge, ecological constraint, formulation performance and commercial viability within a single evidential framework. Existing syntheses characteristically treat one domain in depth and gesture at the others in a concluding paragraph. The result is a literature in which each domain reports progress while the overall translation problem remains unresolved, and in which the specific evidential weaknesses that block translation are neither named nor prioritised. At the broader translational level, recent synthesis also identifies limited long-term in situ evidence, ecological heterogeneity and non-uniform product-development standards as barriers to demonstrating robust microbiome-based performance in agriculture, reinforcing the need for integration across biological and implementation domains (Vompe et al., 2026).

Important exclusions should be stated. This review does not attempt a systematic quantitative synthesis, does not assign formal risk-of-bias scores, and does not evaluate specific commercial products or provide regulatory guidance for any jurisdiction. Economic modelling of market size is outside its scope. The intended contribution is analytical integration and the identification of where the evidence base fails, not exhaustive coverage of an extremely large primary literature.

The objectives are fivefold. First, to evaluate the strength of evidence supporting each principal growth-promotion mechanism, distinguishing demonstrated causation from correlation and mechanistic plausibility. Second, to examine the ecological determinants of inoculant establishment and persistence and to assess how far these explain variable field performance. Third, to appraise formulation science critically, asking whether the reported gains in viability have been shown to translate into agronomic outcomes. Fourth, to analyse production, quality-control and regulatory constraints as scientific problems susceptible to evidence rather than as external obstacles. Fifth, to derive research priorities that follow from the identified weaknesses rather than from general aspiration.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative design was selected because the research question concerns the coherence of an argument that spans molecular biology, soil ecology, materials science, industrial microbiology and regulatory policy. The constituent studies differ so profoundly in design, unit of analysis and outcome measure that quantitative pooling would be inappropriate and a systematic review protocol would either exclude most of the relevant material or produce a heterogeneous set that could not be synthesised meaningfully. The purpose here is interpretive rather than enumerative: to assess whether the field's conclusions follow from its evidence.

Narrative design does not license selective citation or the omission of critical appraisal. The transparency criteria articulated for narrative review quality assessment, which require an explicit justification of importance, a stated aim, a described literature search, appropriate referencing of evidence, and evidence-calibrated presentation of data, were adopted as the working standard for this manuscript (Baethge et al., 2019). The general guidance on narrative review conduct, which emphasises explicit scope, acknowledged

subjectivity and structured argument, informed the organisation of sections (Ferrari, 2015). Conflicting findings are reported where they exist, and the absence of decisive evidence is stated rather than resolved by preference.

2.2 Information Sources

Two scholarly sources were searched directly during preparation of this manuscript: Europe PMC, which indexes MEDLINE and PubMed Central records together with additional life-science content, and Crossref Metadata Search, used both for discovery and for bibliographic verification. Digital Object Identifier resolution through the DOI registry was used to confirm that each cited identifier resolved to the intended article. Subscription databases including Web of Science Core Collection, Scopus and CAB Abstracts were not accessible during this work, and no search of those resources was performed or is claimed. Attempts to query two additional open scholarly indexes were unsuccessful because of service-side request limits, and no results from those services were used.

Foundational and older works identified within the reference lists and discussion sections of retrieved reviews were located by targeted searching of the two accessible sources and verified independently before citation. Where the two sources disagreed on publication year, volume or pagination, the record consistent across both was adopted; where a discrepancy persisted, the publisher-assigned issue metadata was used.

2.3 Search Strategy and Search Period

Search concepts were constructed around five axes: the organism and its designation, the mechanism, the delivery technology, the outcome, and the commercial or regulatory context. Representative strings combined controlled and free-text terms, for example (plant growth promoting rhizobacteria OR PGPR OR bioinoculant OR biofertilizer) AND (formulation OR bioformulation OR encapsulation OR carrier OR seed coating) AND (shelf life OR viability OR survival); (microbial inoculant) AND (field efficacy OR field performance) AND (variability OR inconsistent); (rhizosphere) AND (colonisation OR establishment OR invasion) AND (resident community OR native microbiota); (synthetic microbial community OR SynCom OR consortium) AND (design OR rational OR establishment); and (bioinoculant OR biofertilizer OR biostimulant) AND (regulation OR registration OR commercialisation OR quality control OR adoption). Mechanism-specific strings addressed nitrogen fixation, phosphate solubilisation, aminocyclopropane carboxylate deaminase activity, siderophore production, volatile organic compounds and induced systemic resistance.

The search covered publications from 2012 onward for the principal evidence base, a starting point chosen because the consolidation of mechanistic reviews and the beginning of sustained work on rhizosphere microbiome assembly date from that period and provide the conceptual vocabulary used throughout the current literature. Earlier works were admitted where they remain necessary for historical or conceptual completeness. The final search date was 5 June 2026.

2.4 Eligibility Criteria

Peer-reviewed original research articles and review articles published in English were eligible. Included subject matter comprised the physiology, genetics or ecology of plant-beneficial rhizobacteria; inoculant formulation, carrier science and delivery technology; controlled-environment and field evaluation of inoculant effects on plant growth, nutrient status or stress tolerance; quality assessment of microbial agricultural products; and the regulatory, production and adoption environment for microbial inputs. Studies were excluded when the organisms considered were exclusively fungal, when the application context was non-agricultural, when the report concerned bioremediation without a plant-performance outcome, or when insufficient methodological detail was provided to judge the reliability of the reported result. Preprints, conference abstracts, patents, trade publications and non-peer-reviewed web material were excluded. Sources whose bibliographic identity could not be confirmed through both accessible indexes were not cited.

2.5 Screening, Duplicate Handling and Study Selection

Records retrieved from the two sources were assessed first by title and abstract against the eligibility criteria, and candidates surviving that assessment were examined in full text where accessible. Duplicates arising because the same article was returned by both sources, or by multiple search strings within one source, were identified by Digital Object Identifier and consolidated to a single record. Where an article lacked a Digital Object Identifier in one index, matching was performed on title, first author and journal. Articles that could not be accessed in full text were retained only where the abstract and indexed metadata were sufficient to support the specific claim for which the work is cited, and such use was restricted to descriptive rather than quantitative claims. Language was restricted to English, which constitutes a recognised limitation. No formal screening counts are reported, because the selection process was purposive and iterative rather than systematic, and reporting numerical flow data would misrepresent the method.

2.6 Critical Appraisal and Evidence Synthesis

Each retained study was appraised against criteria appropriate to its design. Controlled-environment work was assessed for the presence of adequate controls, the use of sterile or non-sterile substrate, the number of independent biological replicates, and whether growth-promotion outcomes were separable from nutritional artefacts of the growth medium. Field studies were assessed for the number of site-years, the presence of a fertiliser gradient or other agronomic reference treatment, whether inoculant establishment was verified rather than assumed, and whether yield was measured at harvest under production-relevant management.

Formulation studies were assessed for the duration and temperature range of storage testing, whether viability was reported as colony-forming units per unit mass or volume with a stated enumeration method, and whether any plant outcome was measured using the stored material. Reviews were assessed for scope, transparency of source selection and whether conflicting evidence was represented.

No formal risk-of-bias instrument was applied, since no recognised tool covers this range of designs and the information required to score most studies is not reported. Themes were developed inductively by grouping studies according to the analytical problem they address rather than the organism or crop studied, which allowed evidence from mechanistic, ecological, materials and policy literatures to be compared on the same question. Where studies disagreed, the disagreement was examined for a methodological explanation before any interpretive one was proposed, and where no explanation could be identified the disagreement is reported as unresolved.

3. Mechanistic Foundations and Their Evidential Status

The mechanisms attributed to plant growth-promoting rhizobacteria are conventionally divided into direct effects, which alter nutrient supply or hormonal status, and indirect effects, which reduce biotic pressure. The division is useful for exposition but obscures an important asymmetry: the evidential standards applied to the two classes differ, and within each class the quality of evidence varies by an order of magnitude between mechanisms. This section examines the principal mechanisms with attention to what has actually been demonstrated and at what scale.

3.1 Nitrogen Acquisition and the Persistent Problem of Quantification

Biological nitrogen fixation by free-living and associative diazotrophs has been the most conceptually attractive mechanism since the earliest work on the group, and it remains the least satisfactorily quantified in agricultural settings. The biochemistry is not in doubt, and recent work has clarified how diazotrophic activity is organised in time and space within the plant-associated niche. Engineering of a diazotroph to switch between free-living and nitrogen-donating lifestyles on a diurnal cycle increased nitrogen contribution to cereals under controlled conditions, demonstrating that the constraint is regulatory rather than purely energetic (Tang et al., 2023). Characterisation of the mucilage secreted by the aerial roots of *Sorghum bicolor* showed that this specialised habitat hosts diazotrophs that supply nitrogen to the host, providing an example in which a natural plant structure supports measurable fixation (Venado et al., 2025).

These are advances of genuine significance, and they sharpen rather than resolve the agronomic question. The contribution of associative fixation to a field crop's nitrogen budget under commercial fertilisation remains poorly constrained, and the difficulty is methodological. Isotopic approaches capable of partitioning nitrogen sources at field scale are demanding and infrequently applied, so most reports infer fixation from a growth response or from nitrogenase gene presence, neither of which is a measure of nitrogen transfer. Analyses of the prospects for engineering cereal-associated fixation acknowledge that the gap between demonstrated capacity and delivered nitrogen remains wide, and that closing it requires both host and microbial modification (Chakraborty et al., 2024). In paddy systems, where the biogeochemical setting is more favourable, reviews of biological nitrogen fixation identify the same limitation and emphasise that the sustainable contribution of the process depends on management factors that are rarely controlled in efficacy trials (Zhang et al., 2026). The honest position is that associative fixation is real, that its magnitude under agricultural nitrogen supply is uncertain, and that inoculant products claiming nitrogen benefit are frequently supported by growth data rather than nitrogen data.

3.2 Phosphorus Mobilisation and the Specification of the Limiting Condition

Phosphate solubilisation is mechanistically better resolved than fixation. Organic acid secretion, proton extrusion and phosphatase activity are established routes by which bacteria increase the availability of inorganic and organic phosphorus fractions, and comparative work across taxa has mapped the diversity of these capacities and the conditions under which they operate (Sun et al., 2026). The agronomic evidence is also more favourable, in a specific sense: the global meta-analysis of biofertilisation found that yield responses were greatest where phosphorus availability was low, which is exactly the pattern expected if the mechanism operates as described (Schütz et al., 2018). That result has an implication that the applied literature does not always draw. If the benefit of a phosphate-solubilising inoculant depends on phosphorus limitation, then the appropriate evaluation design includes a phosphorus gradient, and a trial conducted at a single fertility level cannot establish either efficacy or its absence. Very few published field evaluations meet this standard. Work on liquid phosphate-solubilising formulations in potato reported improvements in growth, yield and nutrient content under field conditions, which is useful evidence of a delivered effect, though the design does not permit the mechanism to be isolated from other formulation-associated effects (Bansal et al., 2025). Studies developing phosphate-solubilising *Bacillus* inoculants have concentrated on process parameters affecting production and viability rather than on the agronomic conditions determining response, illustrating how the applied literature tends to optimise what is controllable rather than what is decisive (Bini et al., 2024). Broad syntheses that combine nitrogen-fixing and phosphate-mobilising functions describe both as established contributors to sustainable nutrient management, but the supporting evidence for the two mechanisms is not of comparable strength and the distinction is worth preserving (Rakhmatova et al., 2026).

3.3 Hormonal Modulation and Ethylene Attenuation

Bacterial modification of host hormone status is the mechanism with the clearest link between molecular action and phenotype. Auxin production alters root architecture in ways that increase the absorptive surface, and bacterial aminocyclopropane carboxylate deaminase lowers the ethylene precursor pool and thereby attenuates the growth inhibition associated with stress-induced ethylene accumulation. The conceptual account is long-established (Glick, 2012), and its physiological consequences have been documented across drought, salinity and thermal stress (Pang et al., 2026).

Evidence quality here is better than for fixation but is concentrated in controlled environments. A recent appraisal of aminocyclopropane carboxylate deaminase-producing biostimulants is unusual and valuable in identifying the barriers to deployment explicitly, rather than presenting the mechanism as ready for application, and in noting that translation has been slower than the mechanistic literature implies (Thakur, 2026). The pattern that emerges is instructive: the mechanism most amenable to demonstration in a growth chamber is also the one whose field evidence is thinnest, because the stress conditions under which it operates are precisely those that are hardest to impose reproducibly in the field. Reports of hormonal effects also rarely exclude the possibility that observed root architectural changes reflect nutrient-mediated rather than hormone-

mediated signalling, and dissecting the two requires genetic or chemical intervention that most applied studies do not attempt.

3.4 Volatile Signalling

Bacterial volatile organic compounds have moved from curiosity to a substantiated signalling mechanism. Work demonstrating that a microbial volatile enhances growth in *Arabidopsis* through activation of nitrate and ammonium transport is methodologically strong because it identifies a transport-level target rather than reporting a biomass difference alone (Thida et al., 2026). Comparable evidence in a crop species showed that volatiles from a rhizobacterium mediated salt tolerance in *Brassica napus* with accompanying transcriptomic reprogramming (Wang, Tan, et al., 2026).

The translational difficulty is physical rather than biological. Volatile-mediated effects are typically demonstrated in enclosed systems in which the compound accumulates to a concentration that is unlikely to be sustained in an open soil profile. No published work located in this review followed a volatile-mediated effect from a closed assay to a field outcome, and until such work exists, volatile signalling should be regarded as a demonstrated laboratory mechanism whose agricultural contribution is unquantified. This is not a criticism of the underlying science, which is careful, but of the tendency to list volatile production alongside nutrient mobilisation in accounts of how inoculants benefit crops, as though the two were equally established in the field.

3.5 Biotic Stress Suppression and Immune Priming

Suppression of pathogens through antibiosis, competition and induced systemic resistance is the mechanism with the strongest applied track record, largely because biocontrol products have been evaluated under regulatory schemes that require efficacy data. The molecular understanding of priming has advanced considerably, including recognition of epigenetic components in the primed state (Unal et al., 2026). *Bacillus velezensis* has emerged as a tractable model for plant-associated bacilli, with well-characterised secondary metabolite gene clusters underpinning both antagonism and host interaction (Borriss et al., 2026), and broader appraisals of *Bacillus* as a biocontrol genus link mechanistic detail to application strategy and to the regulatory environment (Hernández-Amador et al., 2026).

An important qualification applies. Priming reduces disease severity under pathogen pressure and confers no yield advantage in its absence, and it may impose a metabolic cost. Trials that report yield benefit from a biocontrol inoculant in the absence of disease assessment cannot distinguish immune priming from other mechanisms, and trials conducted under artificial inoculum pressure may overstate the benefit obtainable under natural infection. The literature would be strengthened by routine reporting of disease incidence alongside yield in all biocontrol evaluations, which remains uncommon.

3.6 The Inferential Gap between Trait and Outcome

A structural weakness runs through the mechanistic literature. The standard experimental sequence isolates a strain, characterises its traits in vitro, sequences its genome, confirms the presence of corresponding genes, and demonstrates a growth response after inoculation. Each step is sound; the conclusion that the characterised trait caused the

growth response does not follow. Establishing causation requires either a mutant lacking the trait, a complementation experiment, or a design in which the resource the trait addresses is manipulated. Such designs appear in a small minority of published studies.

The consequence is that the field possesses a large catalogue of associations and a small body of demonstrated causal relationships, and reviews that summarise the former as though it were the latter propagate the error. The move toward genome-informed selection frameworks partly acknowledges this problem, by treating functional gene content as generating testable hypotheses about performance rather than as evidence of performance (Gonçalves, 2026). Comprehensive recent syntheses of the mechanistic and ecological literature reach broadly consistent conclusions about the range of mechanisms available while differing in how confidently they present the link to field outcomes (Wang & Xu, 2026; Yadav et al., 2026).

Table 1 organises the principal mechanisms according to what has been demonstrated and at what experimental scale, rather than according to biochemical category. The comparison makes visible a gradient that is easily lost in narrative accounts: mechanisms differ not in whether they are real but in how far the evidence extends toward the field. Immune priming and phosphorus mobilisation reach furthest, hormonal modulation occupies an intermediate position with strong physiological support and limited multi-site validation, and volatile signalling and associative nitrogen fixation remain principally supported by controlled-environment work. Reading the table as a hierarchy of evidential maturity rather than of biological importance clarifies where additional field investment would yield the greatest return.

Table 1. Principal growth-promotion mechanisms classified by highest experimental scale at which the effect has been demonstrated

Mechanism	Demonstrated action	Highest scale of demonstration located	Principal evidential weakness	Supporting references
Associative nitrogen fixation	Nitrogenase-mediated dinitrogen reduction; regulated lifestyle switching; colonisation of specialised host habitats	Controlled environment with isotopic or genetic confirmation; natural field habitat characterised	Quantitative contribution to crop nitrogen budgets under commercial fertilisation not established	Chakraborty et al. (2024); Tang et al. (2023); Venado et al. (2025); Zhang et al. (2026)
Phosphorus mobilisation	Organic acid secretion, proton extrusion, phosphatase activity increasing available P	Multi-site field synthesis showing greatest response where P availability is low	Few field trials include a phosphorus gradient, so mechanism is inferred from outcome	Bansal et al. (2025); Bini et al. (2024); Schütz et al. (2018); Sun et al. (2026)
Auxin-mediated root architectural change	Bacterial indole-3-acetic acid altering lateral root density and root surface area	Controlled environment and glasshouse; some field growth responses	Nutrient-mediated and hormone-mediated architectural change rarely separated experimentally	Glick (2012); Vacheron et al. (2013); Vejan et al. (2016)
Ethylene attenuation via ACC deaminase	Cleavage of the ethylene precursor, reducing stress-induced growth inhibition	Controlled-environment stress imposition across drought, salinity and heat	Field stress conditions difficult to impose reproducibly; deployment barriers explicitly unresolved	Glick (2012); Pang et al. (2026); Thakur (2026)
Volatile organic compound signalling	Activation of host nutrient transport; transcriptomic reprogramming under salinity	Closed-chamber assays with molecular target identification	Concentrations achievable in open soil unknown; no traced path to field outcome located	Thida et al. (2026); Wang, Tan, et al. (2026)
Antibiosis and pathogen antagonism	Secondary metabolite production; competitive exclusion at the root surface	Field evaluation under biocontrol registration requirements	Efficacy under natural rather than artificial inoculum pressure less well documented	Borriss et al. (2026); Hernández-Amador et al. (2026)
Induced systemic resistance and priming	Host immune sensitisation including epigenetic components of the primed state	Controlled and field pathosystems with disease severity endpoints	Yield benefit contingent on pathogen pressure; disease incidence often unreported alongside yield	Unal et al. (2026); Wang & Xu (2026)

Note. ACC, 1-aminocyclopropane-1-carboxylate; P, phosphorus. Scale of demonstration refers to the most agronomically realistic setting in which the specific mechanism, rather than a general growth response, has been evidenced within the literature retrieved for this review. Placement reflects evidential maturity and not biological importance

4. Ecological Determinants of Inoculant Performance

If the mechanistic account is sound, the recurrent failure of inoculants to perform in the field requires an explanation located elsewhere. The ecological literature supplies the most coherent one: an introduced strain must establish, persist and remain metabolically active at the root surface in an environment already occupied, and the probability of doing so is governed by processes that strain selection alone does not address.

4.1 Establishment as an Invasion Problem

Framing inoculation as a biological invasion has proved analytically productive. The application of macroecological models to predict establishment probability in an agricultural inoculant introduction represents a methodological advance, because it converts an intuitive expectation of decline into a quantitative prediction that can be tested (Klimasmith et al., 2024). This reframing implies that inoculum dose, timing and the resident community's structure are not incidental application details but primary determinants of outcome. It also implies that the conventional practice of reporting inoculum concentration without measuring subsequent population density leaves the central variable unobserved.

Direct measurement supports the pessimistic expectation. Tracking of a candidate bacterial biocontrol agent in soil showed measurable decline and documented the accompanying effects on resident microbial communities, providing the kind of temporal data that most inoculant studies omit (Polrot et al., 2026). The broader ecological synthesis of interactions determining the establishment and function of synthetic consortium inoculants in soil applications identifies interspecific interaction, rather than intrinsic strain fitness, as the dominant control on establishment (Xu et al., 2025). This is a substantial claim with practical consequences: a strain screened in monoculture for growth rate and trait expression is being evaluated on a criterion that ecological analysis suggests is not the limiting one.

4.2 Interaction with the Resident Community

The resident rhizosphere community is both the obstacle to establishment and, potentially, the medium through which inoculant effects are realised. Its composition is not arbitrary: root-associated assemblages are structured by host selection acting on a soil-derived pool, and the resulting community mediates plant health through processes that operate at community rather than population level (Trivedi et al., 2020). An introduced strain therefore encounters an assemblage assembled under selection that it did not experience. Analysis of interactions between rhizobacteria of the phylum *Bacillota* and native rhizosphere microbiota emphasises that outcomes depend on the compatibility of the introduced organism with the existing assemblage rather than on its properties in isolation (Szpytma & Dobrzyński, 2026). Experimental work in barley demonstrated that interbacterial antagonism within synthetic communities mediated the resulting plant growth modulation, showing that antagonistic interactions among introduced strains can determine the plant-level outcome (Mahamud et al., 2026).

An interpretive tension exists in this literature. One position treats the resident community as a barrier to be overcome by higher inoculum dose or better colonisation traits. Another treats inoculation as a perturbation whose value lies in shifting community composition, so that the introduced strain need not persist for the benefit to be realised.

The two positions predict different experimental signatures: the first requires a correlation between inoculant density and plant response, the second permits benefit without persistence. Studies designed to distinguish them are rare, and the ambiguity partly explains why field results resist interpretation. Field-scale work measuring soil enzymatic activities and microbial indicators after combined bioinoculant and fertiliser management in mustard, *Brassica juncea* L., illustrates the community-level response that inoculation can produce, though such designs do not by themselves resolve whether the plant benefit is mediated by persistence or by perturbation (Singh et al., 2026).

4.3 Context Dependency and the Environment as an Experimental Factor

The strongest quantitative evidence in the field concerns context dependency. Yield benefit is greatest where an environmental constraint exists that the inoculant mechanism can relieve, and diminishes toward zero as constraints are removed (Rubin et al., 2017; Schütz et al., 2018). A meta-analysis focused on rhizobacterial interaction with host plants under drought found consistent effects on stress-response gene expression, supporting the interpretation that the response is conditional on stress rather than general (Ferrante et al., 2024).

This is the most agronomically consequential finding in the literature, and its implications for evaluation design are widely ignored. If the effect is conditional, single-site trials are uninformative about the technology and informative only about that site. Multi-environment trial designs with formal genotype-by-environment analysis are standard in crop breeding and almost absent from inoculant evaluation. Their absence means that the field cannot presently distinguish a strain that performs well in a narrow environmental band from one that performs moderately across a wide band, which is precisely the distinction a farmer or a registrant needs. Recognising that environmental variation is a factor to be designed for rather than a nuisance to be averaged away is a prerequisite for progress. An emerging alternative approach inverts the screening logic by recruiting candidates from rhizospheres already subject to the target stress, so that environmental filtering has been performed by the system before laboratory screening begins (Niraula et al., 2026).

Table 2 assembles the principal points of disagreement in the field-performance literature alongside the methodological features that most plausibly explain them. Its purpose is diagnostic. In each case a candidate methodological explanation exists, and in each case a design capable of testing that explanation can be specified, which suggests that the disagreements reflect evaluation practice more than irreducible biological complexity. Where a disagreement cannot yet be attributed to design, this is stated rather than resolved by preference.

Table 2. Recurrent disagreements in the inoculant performance literature and their candidate methodological explanations

Point of disagreement	Contrasting positions	Most plausible methodological explanation	Design that would discriminate	Supporting references
Magnitude of yield benefit	Substantial and agronomically meaningful versus modest and inconsistent	Aggregation across environments with differing degrees of nutrient or water limitation conceals a conditional effect	Multi-environment trials with explicit environmental covariates and genotype-by-environment analysis	Rubin et al. (2017); Schütz et al. (2018)
Necessity of inoculant persistence	Benefit requires sustained root colonisation versus benefit arises from transient community perturbation	Persistence is rarely measured, so both interpretations remain consistent with published outcomes	Time-series quantification of the introduced strain alongside plant response in the same experiment	Klimasmith et al. (2024); Polrot et al. (2026); Xu et al. (2025)
Value of multi-strain consortia	Consortia outperform single strains versus consortia introduce antagonism and dilute the effective dose	Consortium composition is usually assembled on trait complementarity without testing interspecific compatibility	Factorial comparison of members alone and in combination with interaction quantification	Belda (2026); Mahamud et al. (2026); Xu et al. (2025)
Reliability of in vitro trait screening	In vitro traits predict field performance versus screening selects for laboratory fitness	Screening conditions differ fundamentally from the rhizosphere in resource form and competitive context	Prospective comparison of in vitro rank order with field rank order in the same strain panel	Gonçalves (2026); Niraula et al. (2026); Sadanov et al. (2026)
Contribution of associative nitrogen fixation	Agronomically significant nitrogen input versus negligible under commercial fertilisation	Growth responses are widely used as proxies for nitrogen transfer, which they do not measure	Isotopic partitioning of crop nitrogen at field scale across a nitrogen fertiliser gradient	Chakraborty et al. (2024); Tang et al. (2023); Zhang et al. (2026)
Consistency of commercial product performance	Variable field results reflect biological context versus variable product composition and viability	Independent verification of marketed product content is scarce for bacterial inoculants	Blinded independent assay of viable declared organisms in marketed products before field testing	Koziol et al. (2024); Singtothong et al. (2026)

Note. Positions are stated as they appear in the literature and are not endorsed. Discriminating designs are those that would render the competing positions empirically separable using currently available methods

5. Strain Discovery, Consortium Design and the Problem of Identity

5.1 The Predictive Weakness of Conventional Screening

The dominant discovery pipeline has changed little in three decades. Isolates are recovered from a rhizosphere, screened on defined media for phosphate solubilisation, siderophore production, indoleacetic acid synthesis and aminocyclopropane carboxylate deaminase activity, ranked by the strength of these responses, and the highest-ranking isolates are advanced to plant testing. The approach has produced most of the strains now in commercial use, and its limitations are structural rather than incidental.

Screening media present resources in forms and concentrations that do not occur in soil, and they impose no competition. A strain that solubilises tricalcium phosphate vigorously on agar is being assessed under conditions that reward a phenotype which may be neither expressed nor advantageous in the rhizosphere. Recent process-oriented work on strain selection and production organisation for microorganism-based agricultural products makes the pipeline explicit and, in doing so, exposes how early screening decisions constrain everything downstream (Sadanov et al., 2026). The alternative of ecological pre-selection, in which candidates are recovered from plants already thriving under the target stress, applies the relevant filter before laboratory screening and has yielded candidates including a proposed novel *Paracoccus* species from drought-exposed tomato rhizospheres (Niraula et al., 2026). Whether ecologically pre-selected strains outperform conventionally screened ones has not been tested prospectively, and the comparison would be straightforward to make.

5.2 Genome-informed Selection

Genomic characterisation has become routine and its interpretation has become more disciplined. Early practice treated the detection of nitrogen fixation or phosphate solubilisation genes as confirmation of function. A genome-first framework for next-generation bioinputs recasts functional mining as the generation of ranked hypotheses about performance, to be tested rather than assumed, and explicitly connects mining to the rational design of synthetic communities (Gonçalves, 2026). This is a meaningful shift in epistemic standard, and it has an important corollary: genome content can efficiently exclude candidates, since a strain lacking the relevant biosynthetic capacity can be set aside with confidence, while inclusion on genomic grounds alone remains unsupported. Detailed genomic and functional characterisation of model organisms such as *Bacillus velezensis* provides the reference against which such inferences can be calibrated (Borriss et al., 2026).

5.3 Consortia and the Ecology of Assembly

Multi-strain products are commercially prevalent and the rationale offered for them is usually functional complementarity, so that one member fixes nitrogen, another mobilises phosphorus and a third antagonises pathogens. This rationale assumes additivity, and the ecological evidence contradicts the assumption. Interspecific interaction rather than individual capability determines establishment and function in soil-applied consortia (Xu et al., 2025), and antagonism among members has been shown to mediate the plant growth outcome directly (Mahamud et al., 2026). A framework drawing explicitly on

ecological theory for the design of industrial microbial consortia argues that community assembly principles, rather than trait inventories, should govern composition (Belda, 2026).

Iterative selection offers a partial alternative to rational design. A synthetic community for soybean biofertilisation was assembled through chlorophyll-based iterative selection, using a host physiological readout to guide composition rather than specifying members in advance (Brignoli et al., 2026). The approach sacrifices mechanistic interpretability for empirical performance, which is a defensible trade in an applied context. Broader accounts of rhizosphere microbiome engineering, including proposals to integrate consortium design with decision-support systems, extend the ambition considerably (Fouad et al., 2026), and related syntheses on bioengineered rhizospheres and on plant microbiome engineering from inoculation through to genome editing describe a technological trajectory whose field validation remains at an early stage (Adhikary et al., 2026; Yadav et al., 2026). The proposal that microbiomes might be bred, in analogy with host breeding, using heritable community-level variation, is conceptually attractive and its practical feasibility is not yet demonstrated (De Zutter & Audenaert, 2026).

5.4 Taxonomic Instability and the Traceability of Strains

An underappreciated problem cuts across discovery, regulation and literature synthesis. Phylogenomic reassessment has substantially revised bacterial taxonomy in genera central to this field, with the demarcation of seventeen distinct *Bacillus* clades and their proposal as novel genera within the *Bacillaceae*, restricting *Bacillus* to members of the Subtilis and Cereus clades (Gupta et al., 2020). Organisms long designated *Bacillus megaterium* and *Bacillus aryabhattai* are now placed in *Priestia*, among other reassignments.

The practical consequences are not trivial. Literature searches keyed to the former name miss subsequent work, product labels and registration dossiers may carry superseded designations, and comparison of results across studies published before and after the revision requires care that is not always exercised. For a field in which the identity of the active ingredient is the product, nomenclatural drift is a quality-assurance issue rather than a taxonomic nicety. Consistent reporting of strain identifiers, genome accessions and current nomenclature alongside the name used at the time of isolation would resolve the difficulty at negligible cost, and remains uncommon.

Table 3 contrasts the three selection paradigms currently in use with respect to what each assumes, what it can establish and where it fails. The comparison indicates that the paradigms are complementary rather than competing: genomic mining excludes candidates efficiently, ecological pre-selection improves the environmental relevance of the starting panel, and iterative functional selection optimises performance without requiring mechanistic understanding. No published study located in this review applied more than one paradigm to the same strain panel, so their relative and combined value remains untested.

Table 3. Comparison of strain and consortium selection paradigms by underlying assumption, evidential yield and principal failure mode

Paradigm	Core assumption	What it can establish	Principal failure mode	Supporting references
In vitro trait screening	Trait expression on defined media predicts rhizosphere function	Presence of a metabolic capacity under permissive conditions	Rewards laboratory fitness; imposes no competitive or resource-form realism	Sadanov et al. (2026); Vejan et al. (2016)
Genome-informed functional mining	Genetic potential constrains, but does not confer, realised function	Reliable exclusion of candidates lacking required capacity; ranked hypotheses for testing	Inclusion on genomic evidence alone remains unvalidated; regulation and expression not captured	Borriss et al. (2026); Gonçalves (2026)
Ecological pre-selection from stressed rhizospheres	Environmental filtering by the target stress precedes and improves on laboratory screening	Candidates demonstrably persisting under the intended deployment condition	Prospective comparison against conventional screening has not been performed	Niraula et al. (2026)
Rational consortium assembly on trait complementarity	Member functions combine additively at the plant level	Coverage of multiple nutrient or protective functions in principle	Assumes additivity; interspecific antagonism can reverse the plant-level outcome	Belda (2026); Mahamud et al. (2026); Xu et al. (2025)
Iterative selection on a host readout	Host physiological response is a sufficient objective function for composition	Empirically optimised communities without prior mechanistic specification	Mechanism remains opaque; transferability across soils and cultivars untested	Brignoli et al. (2026)
Community-level breeding of microbiomes	Community composition carries heritable, selectable variation affecting host performance	A conceptual route to durable community-level improvement	Feasibility at agronomic scale not yet demonstrated	De Zutter & Audenaert (2026)

Note. Paradigms are not mutually exclusive. No study retrieved for this review applied more than one paradigm to a common strain panel, so relative performance is inferred from design characteristics rather than from direct comparison

6. Formulation Science: Achievement and Unverified Inference

Formulation converts a laboratory culture into a product that can be stored, transported, applied with existing machinery and delivered to the root in viable condition. The comprehensive assessment of inoculant technology covering the period from 1998 to 2013 established the framework still used, distinguishing carrier-based solid formulations, liquid preparations and encapsulated systems, and identified the loss of viability during storage and application as the recurrent technical constraint (Bashan et al., 2014). More than a decade later, subsequent syntheses of bioformulation approaches describe an expanded materials repertoire while identifying substantially the same constraint, which itself indicates the pace of genuine progress (Khan et al., 2023).

6.1 Solid Carriers

Peat has dominated solid formulation because it protects cells physically, buffers moisture and pH, and supports survival for months. Its disadvantages are equally durable: extraction carries environmental costs, quality varies between deposits, sterilisation is required, and supply is geographically constrained. Work with peat-based bioformulations of microbial co-inoculants combined with silicon reported growth promotion in rubber plants, illustrating that the platform continues to support functional products and that carrier amendment can be used to add non-biological function (Ling et al., 2025).

Alternative carriers have been evaluated principally on cost and local availability. Coconut coir dust was assessed as a biofertiliser carrier for coffee seedlings, with growth and nutrient uptake as endpoints (Chromkaew et al., 2023), and actinomycete consortia formulated using low-cost dynamic media were characterised for shelf life (Moorthy et al., 2025). These studies address a real constraint in production regions where peat is unavailable. They also illustrate a general weakness in the carrier literature: each evaluates a single carrier in a single system, so the accumulated evidence permits no ranking of carriers under comparable conditions. A standardised comparative protocol applying the same strains, storage regimes and enumeration methods across candidate carriers would be inexpensive and would resolve a question that dozens of individual studies have left open.

6.2 Liquid Formulations

Liquid formulations avoid carrier sourcing and sterilisation, simplify manufacturing and integrate with existing spray and fertigation equipment. Their weakness is that cells remain metabolically active and therefore consume reserves and accumulate metabolites during storage, so shelf life is typically shorter and more temperature-sensitive unless osmoprotectants or physiological pre-conditioning are used. Field evaluation of a liquid phosphate-solubilising formulation in potato reported improvements in growth, yield and nutrient content, which demonstrates that the format can deliver an agronomic result (Bansal et al., 2025). Whether the format is inferior to solid carriers under equivalent supply-chain conditions has not been established comparatively, and the choice between formats in commercial practice appears to be driven by manufacturing convenience and market expectation rather than by demonstrated performance.

6.3 Encapsulation and Polymeric Delivery

Encapsulation within polymer matrices addresses the viability problem directly by isolating cells from desiccation, ultraviolet radiation and antagonists while permitting controlled release. Development of a multifactorial formulation for stable encapsulation of plant growth-promoting microorganisms represents the more rigorous end of this literature, in that multiple formulation variables were optimised jointly rather than sequentially (Dolatabad, 2026). Hydrogel systems have attracted parallel interest: pullulan-based hydrogels synthesised at room temperature were developed for controlled delivery of microbial fertilisers, with the synthesis conditions themselves relevant because thermal processing damages cells (Erceg et al., 2025), and a broader appraisal of hydrogels in agriculture places microbial delivery within the wider context of soil amendment and crop enhancement (Wang, Hu, et al., 2026). Immobilisation of a biostimulator consortium on bacterial cellulose was evaluated with onion growth, soil nutrient status and microbial community composition as endpoints, which is a more complete outcome set than most formulation studies report (Yaseen, 2026).

Three limitations recur across this body of work. Storage testing is commonly conducted at a single temperature for a period shorter than a commercial shelf life, whereas products encounter variable and often elevated temperatures in distribution. Cost of goods is rarely reported, although encapsulation materials and processing are the principal determinants of whether a formulation can be manufactured at a price agriculture will bear. Most importantly, viability is treated as the terminal endpoint. Demonstrating that encapsulation preserves cells does not demonstrate that the preserved cells colonise roots, and the intermediate step is almost never measured. The inference from viability to agronomic benefit is therefore an assumption embedded in the design of most formulation research rather than a finding of it.

6.4 Seed-applied Delivery

Seed treatment is the most efficient delivery route in principle, placing organisms at the point of root emergence with minimal material. It is also the most demanding, because the coating must survive seed processing, storage and sowing while sustaining viability on a surface that is dry and often chemically treated. Silk-trehalose seed coating technology was shown to preserve *Rhizobium tropici* viability and to enhance zinc biofortification in common bean under marginal soil conditions, a study notable because it followed the technology from coating through survival to a compositional outcome in the harvested product (Mhada et al., 2026).

That study is unusual precisely because it closes the chain of inference that most formulation research leaves open. Its subject is a rhizobial symbiont rather than a free-living rhizobacterium, so the establishment step is assisted by nodulation and the result cannot be extrapolated directly. It nonetheless demonstrates the design that the formulation literature requires: a single experimental system in which storage, delivery, establishment and a plant-level outcome are measured together. Compatibility with agrochemical seed treatments, which determines whether a biological product can be used within conventional seed systems, is acknowledged as a constraint across the formulation literature and is seldom quantified for specific product combinations.

Table 4. Formulation platforms compared by operational characteristics and by the evidential step that remains unclosed

Platform	Principal advantage	Principal constraint	Evidential step not closed in retrieved studies	Supporting references
Peat and other solid carriers	Physical protection, moisture and pH buffering, extended survival	Environmental cost of extraction, variable deposit quality, sterilisation requirement, geographical supply limits	No standardised comparison of carriers under common strains, storage regimes and enumeration methods	Bashan et al. (2014); Ling et al. (2025)
Low-cost agro-residue carriers	Local availability and reduced cost in production regions lacking peat	Compositional variability between batches and sources; limited characterisation	Single-carrier, single-system designs prevent ranking against conventional carriers	Chromkaew et al. (2023); Moorthy et al. (2025)
Liquid formulations	Simplified manufacture; compatibility with spray and fertigation equipment	Continued metabolic activity during storage; greater temperature sensitivity	No controlled comparison with solid carriers under equivalent supply-chain conditions	Bansal et al. (2025); Khan et al. (2023)
Polymer encapsulation	Isolation from desiccation and antagonists; controlled release	Materials and processing cost; scale-up of encapsulation equipment	Viability treated as terminal endpoint; root colonisation from encapsulated cells not measured	Dolatabad (2026)
Hydrogel delivery systems	Moisture retention at the delivery site; ambient-temperature synthesis avoids thermal damage	Field persistence of the matrix and behaviour across soil textures poorly characterised	Agronomic outcomes from hydrogel-delivered inoculants under field conditions not established	Erceg et al. (2025); Wang, Hu, et al. (2026)
Immobilisation on biopolymer supports	Structural protection with reported effects on soil nutrient status and community composition	Production cost of the support material at agricultural scale	Comparative advantage over conventional carriers not quantified	Yaseen (2026)
Seed coating	Minimal material requirement; organisms placed at the point of root emergence	Survival through processing, storage and sowing; compatibility with chemical seed treatments	Demonstrated for a rhizobial symbiont; equivalent chain of evidence for free-living strains not located	Mhada et al. (2026)

Note. The evidential step column identifies what the retrieved literature does not establish, not a deficiency of any individual study. Platforms are not mutually exclusive and are frequently combined in commercial products

6.5 The Absent Standard

Comparison across formulation studies is impeded by the absence of reporting conventions. Viable counts are expressed variously per gram, per millilitre, per seed or per hectare; enumeration may use plate counts, most probable number estimation or quantitative polymerase chain reaction, which are not interchangeable; storage duration and temperature vary without justification; and the criterion for acceptable shelf life is rarely stated. A minimum reporting set specifying enumeration method, storage temperature range, duration, viability at defined intervals and the density delivered at the point of application would permit the comparative synthesis that is presently impossible. This is a coordination problem rather than a scientific one, and its persistence is the more striking for that.

Table 4 compares formulation platforms on the dimensions that determine practical viability and identifies, for each, the specific evidential step that remains unclosed. The pattern is consistent: every platform has demonstrated viability preservation, and only the seed-coating example located here traced that preservation through to a measured plant-level outcome within the same experimental system. The table therefore documents a shared structural weakness rather than a ranking of technologies, and the entries in its penultimate column define the studies the field most needs.

7. Field Performance: Magnitude, Variability and the Quality of Agronomic Evidence

The quantitative evidence on field performance is smaller and less consistent than the volume of publication suggests, because most reports concern controlled environments and most field reports concern single sites. The syntheses that do exist converge on a coherent picture. Biofertilisation raises yield and nutrient use efficiency on average, with the magnitude conditioned by climate and soil phosphorus status (Schütz et al., 2018), and rhizobacterial inoculation is more effective under drought than under adequate water supply (Rubin et al., 2017). Drought-focused synthesis of host gene expression responses supports the interpretation that the underlying physiological effect is stress-conditional (Ferrante et al., 2024).

Individual field studies published since add detail without altering the picture. Evaluation of multiple multifunctional inoculants in soybean under field conditions provides the kind of comparative product assessment that is uncommon in the literature and that reveals differences between commercially available preparations (Mirza et al., 2026). Combined bioinoculant and fertiliser management in mustard produced measurable responses in soil enzymatic activities and microbial indicators at field scale, demonstrating that inoculation produces detectable soil biological change under production conditions even where the pathway to yield is not resolved (Singh et al., 2026).

Four methodological weaknesses limit what can be concluded from the field literature as a whole. Site-years are few, so environmental variance is undersampled and effect estimates are imprecise. Inoculant establishment is rarely verified, so a null result cannot be attributed to biological ineffectiveness rather than delivery failure, and the two require entirely different responses. Fertiliser gradients are seldom included, so the conditionality demonstrated meta-analytically cannot be examined within individual trials. Publication

of negative results appears limited, which is difficult to demonstrate directly but is suggested by the scarcity of published trials reporting no effect in a field where practitioners describe inconsistent performance as routine; the potential for publication bias to inflate summary estimates should be assumed rather than dismissed.

An additional consideration concerns unintended effects. Analysis of the dual nature of plant growth-promoting bacteria draws attention to risks that accompany deployment, including effects on non-target organisms and the possibility that beneficial designation obscures context-dependent harm (Etesami, 2025). Assessment of microbial inoculants as biostimulants from a risk perspective reaches compatible conclusions regarding the need for systematic evaluation rather than presumption of safety (Kumari et al., 2023). Documented decline of an introduced biocontrol agent accompanied by measurable effects on resident communities confirms that introduction is not ecologically neutral even when the introduced population does not persist (Polrot et al., 2026). Efficacy and safety evidence should therefore be generated within the same trials rather than in separate literatures.

8. Production, Quality Assurance, Regulation and Market Formation

8.1 Production Systems and the On-farm Alternative

Industrial production requires fermentation processes that deliver high cell densities of the specific strain while maintaining the physiological state that supports subsequent survival, followed by concentration and formulation without excessive loss. Analysis of production organisation for microorganism-based agricultural products treats these steps as an integrated system in which strain selection constrains downstream processing (Sadanov et al., 2026). Development of the biofertiliser industry in China illustrates what sustained industrial and research investment produces at national scale, including consolidation of manufacturing capacity alongside a research programme (Sun et al., 2025).

On-farm production has emerged as a substantial parallel system in some agricultural economies, and its analysis alongside commercial production within a specific regulatory framework identifies the resulting tension clearly: on-farm production reduces cost and improves access while making quality control and traceability considerably harder to achieve (Xavier et al., 2026). The scientific question this raises is whether products of on-farm systems achieve comparable cell densities, purity and agronomic effect, and comparative data addressing it are scarce. The regulatory question is whether a framework designed for manufactured products can accommodate a decentralised system without either suppressing it or abandoning quality assurance.

8.2 Quality Assurance and the Integrity of the Product

Quality failure is the most direct threat to the credibility of this technology, because a product that does not contain viable declared organisms cannot perform regardless of the underlying science, and repeated field failure attributable to product quality will be attributed by users to the technology. The independent assessment of twenty-three mycorrhizal inoculants, which found limited viability of the declared fungi, contamination with plant pathogens and in some cases negative effects on crop growth, is

the most direct available evidence that this risk is realised in marketed products (Koziol et al., 2024). The finding concerns fungal products and cannot be transferred to bacterial inoculants without evidence, but the absence of comparable published surveys of bacterial products is itself informative, since it indicates that the corresponding verification has not been performed and published rather than that it has been performed and found satisfactory.

Analytical capability is not the obstacle. Application of recombinant antibodies to quality control of mixed-culture peanut bradyrhizobial inoculant demonstrates that strain-specific detection within a multi-strain product is technically achievable (Singtothong et al., 2026). Molecular quantification of specific strains in complex matrices is routine in other sectors. The constraint is that quality verification is neither routinely required by regulation nor routinely reported by manufacturers, so the methods exist and are not systematically applied.

8.3 Regulatory Architecture

Microbial agricultural inputs occupy an awkward regulatory position because they are living organisms whose effects depend on establishment in an uncontrolled environment, yet they are regulated within frameworks designed for chemical fertilisers or pesticides. Analysis of next-generation biostimulants addresses regulatory frameworks alongside the underlying science and identifies fragmentation across jurisdictions as a structural impediment to development (Mashabela et al., 2025). Regulatory considerations are addressed within appraisals of *Bacillus* biocontrol agents as an integral component of deployment strategy rather than as an afterthought (Hernández-Amador et al., 2026), and the Brazilian framework has been analysed specifically in relation to the coexistence of commercial and on-farm production (Xavier et al., 2026).

Comparison with the adjacent biopesticide sector is instructive. Analysis of why microbial biopesticide development and uptake have not matched expectations argues for reconsideration of development pathways rather than incremental adjustment, and the diagnosis applies with little modification to growth-promoting inoculants: registration costs are high relative to market size, efficacy data requirements are poorly matched to context-dependent products, and the resulting incentive structure discourages the multi-environment evaluation that would establish where products work (Glare et al., 2026). The development of mycoinsecticides, examined in relation to formulation advances, regulatory challenges and market trends, exhibits the same pattern of technical progress constrained by registration and market structure (Couceiro et al., 2026). Where genetically engineered organisms are involved, food safety considerations introduce an additional regulatory layer whose requirements have been examined for microbial crop protection agents and biostimulants (van der Berg et al., 2025). Risk assessment of microbial inoculants as biostimulants indicates that systematic evaluation frameworks remain incompletely developed even for non-engineered organisms (Kumari et al., 2023).

Table 5. Commercialisation constraints, the evidence establishing them, and the current status of that evidence

Constraint	Nature of the problem	Evidential status	Priority action indicated	Supporting references
Product quality and viable content	Marketed products may contain insufficient viable declared organisms or contaminants	Documented directly for commercial mycorrhizal products; equivalent published survey for bacterial inoculants not located	Independent blinded survey of marketed bacterial inoculants using strain-specific enumeration	Koziol et al. (2024); Singtothong et al. (2026)
Absence of standardised viability reporting	Enumeration methods, storage conditions and shelf-life criteria are reported inconsistently	Inferred from the incomparability of retrieved formulation studies rather than formally assessed	Adoption of a minimum reporting set for viability, storage regime and delivered dose	Bashan et al. (2014); Khan et al. (2023)
Regulatory fragmentation across jurisdictions	Divergent classification and data requirements raise cost and impede transfer between markets	Described consistently across regulatory analyses in multiple jurisdictions	Comparative analysis of registration outcomes under differing data requirements	Glare et al. (2026); Mashabela et al. (2025); Xavier et al. (2026)
Mismatch between efficacy standards and conditional performance	General efficacy requirements suit products with context-independent effects	Supported indirectly by meta-analytic evidence of environmental conditionality	Development of condition-specified efficacy claims tied to defined environmental criteria	Rubin et al. (2017); Schütz et al. (2018)
Registration economics relative to market size	Data and registration costs are high relative to achievable revenue, especially for minor crops	Argued in detail for microbial biopesticides and entomopathogenic fungal products	Analysis of proportionate data requirements scaled to exposure and market scope	Couceiro et al. (2026); Glare et al. (2026)
Quality control in on-farm production	Decentralised production improves access while complicating traceability and verification	Framework tension described; comparative performance data against commercial products scarce	Paired comparison of on-farm and commercial products for cell density, purity and field effect	Sadanov et al. (2026); Xavier et al. (2026)

Constraint	Nature of the problem	Evidential status	Priority action indicated	Supporting references
Adoption and profitability evidence	Farm-level economic returns and the determinants of adoption are largely uncharacterised	One matched-design national study located; general evidence base thin	Multi-country farm-level economic analysis across contrasting production systems	Chala et al. (2025)
Non-target and ecological effects	Introduction alters resident communities; risk frameworks remain incompletely developed	Effects on resident communities demonstrated; systematic risk assessment frameworks incomplete	Integration of non-target monitoring into efficacy trials rather than separate assessment	Etesami (2025); Kumari et al. (2023); Polrot et al. (2026)

Note. Evidential status describes the strength of published support located in this review and is not a judgement of whether the constraint is real. Priority actions are those indicated by the identified evidence gap

A regulatory design tension runs through this literature and is rarely stated plainly. Requiring efficacy evidence raises registration costs and restricts market entry, particularly for small developers and for products aimed at minor crops or specific regions. Not requiring it permits products of unverified performance to reach farmers and, over time, degrades confidence in the entire category. Neither position is straightforwardly correct, and the choice between them is a policy judgement informed by, but not determined by, scientific evidence. What the evidence does support is that context-conditional efficacy requires a data standard framed in terms of specified conditions rather than general effect, and no jurisdiction identified in this review has adopted such a standard.

8.4 Adoption and the Thinness of Economic Evidence

Adoption evidence is the weakest link in the entire chain. Assessment of biofertiliser technology adoption and its effect on faba bean productivity in the central highlands of Ethiopia, using propensity score matching to address selection into adoption, is valuable precisely because such analyses are rare (Chala et al., 2025). Single-country studies of one crop cannot support general conclusions, and the paucity of comparable work means that the economic case for adoption rests largely on assumption.

This matters for the scientific programme and not only for commerce. Farmers assess an input on cost, reliability and compatibility with existing operations. A product delivering a modest yield gain in favourable conditions and none in unfavourable ones presents an economic proposition quite different from one delivering a consistent smaller gain, and the two require different research strategies. Without adoption and profitability evidence, the field cannot determine which performance profile it should be optimising, and continues to optimise mean response in the absence of information about what users require.

Table 5 links each principal commercialisation constraint to the specific evidence that establishes it and to the current status of that evidence. Its purpose is to separate constraints that are well documented from those that are asserted repeatedly but supported thinly. Quality failure in marketed products and regulatory fragmentation are documented, though for quality the direct evidence concerns fungal rather than bacterial products. Adoption economics and the comparative performance of on-farm production are among the most consequential constraints and among the least investigated, which identifies them as priorities for work that is neither technically demanding nor expensive.

9. Future Directions

The priorities set out below follow from the evidential weaknesses identified in the preceding sections rather than from general aspiration. They are ordered by the ratio of expected gain to the difficulty of execution, and the first three could be undertaken with existing methods and modest resources.

9.1 Multi-environment Evaluation with Formal Environmental Analysis

The unresolved problem is that inoculant efficacy is conditional on environment, and the field cannot presently specify the conditions under which a given product works. Current evidence is inadequate because it consists predominantly of single-site trials whose

results cannot be generalised and meta-analyses that identify conditionality without characterising it at a resolution useful to a farmer or a registrant. The appropriate design is the multi-environment trial series established in crop breeding, in which the same strains and formulations are evaluated across sites selected to span the relevant environmental gradients, with genotype-by-environment interaction analysed formally and environmental covariates measured at each site. Sites should span soil phosphorus availability, nitrogen management intensity and water regime, since these are the gradients across which conditionality has been demonstrated (Rubin et al., 2017; Schütz et al., 2018). Outcome measures should include yield at harvest, crop nutrient uptake and verified inoculant establishment, so that a null result can be attributed correctly. Such work would materially advance the field by converting a general claim of context dependency into a predictive statement about where a product is likely to work, which is the information both registration and extension require.

9.2 Closing the Chain from Formulation to Field Outcome

The unresolved problem is that formulation research demonstrates viability preservation and infers agronomic benefit. Current evidence is inadequate because storage, colonisation and yield are almost never measured within the same experimental system, so the inference is untested. The required design is straightforward: a single study in which formulated material is stored under a defined regime, sampled at intervals for viability, sown or applied at those intervals, and evaluated for both root colonisation and plant performance. The seed-coating study that traced viability preservation through to a compositional outcome in harvested grain demonstrates that such designs are achievable, and its extension to free-living rhizobacteria and to non-leguminous hosts is the obvious next step (Mhada et al., 2026). The timescale should match commercial shelf-life expectations rather than the convenience of an experimental cycle, and temperature regimes should reflect distribution conditions in the target market rather than laboratory ambient conditions.

9.3 Independent Verification of Marketed Product Composition

The unresolved problem is that the composition and viability of marketed bacterial inoculants are not independently verified, and quality failure would produce field results indistinguishable from biological ineffectiveness. Current evidence is inadequate because the only comparable published survey concerns mycorrhizal products (Koziol et al., 2024). The appropriate study is a blinded independent survey of commercially available bacterial inoculants purchased through normal retail channels in several jurisdictions, assayed for viable count of the declared organism, strain identity confirmed by molecular methods, and presence of contaminants. Strain-specific detection within mixed-culture products is technically established (Singtothong et al., 2026). Such a survey would either substantially reassure the sector or identify a problem whose correction is a precondition for progress, and either outcome would be more valuable than the present uncertainty. The policy implications are immediate, since a demonstrated quality problem would justify mandatory verification requirements that are difficult to argue for in the absence of evidence.

9.4 Ecological Design and Testing of Consortia

The unresolved problem is that multi-strain products are assembled on assumptions of functional additivity that ecological evidence contradicts. Current evidence is inadequate because consortium studies rarely include the factorial comparisons required to separate interaction effects from additive ones. The appropriate design tests each member individually and in all relevant combinations, quantifies interspecific interaction directly, and measures establishment of each member alongside the plant response. Theoretical frameworks for consortium design drawing on ecological principles exist and are ready for empirical evaluation (Belda, 2026; Xu et al., 2025), as does experimental evidence that antagonism among members determines the plant outcome (Mahamud et al., 2026). Iterative selection on a host readout provides a complementary route that does not require prior mechanistic specification and merits direct comparison with rationally assembled consortia in the same system (Brignoli et al., 2026).

9.5 Resolving the Contribution of Associative Nitrogen Fixation

The unresolved problem is the quantitative contribution of associative fixation to crop nitrogen under agricultural management. Current evidence is inadequate because growth responses are widely used as proxies for nitrogen transfer, which they do not measure, and because isotopic partitioning at field scale is rarely attempted. The appropriate work applies isotopic methods across a nitrogen fertiliser gradient in the target crop and environment, with nitrogenase activity and diazotroph population density measured concurrently. The advances in understanding the regulation and habitat requirements of diazotrophic activity provide the mechanistic basis for interpreting such measurements (Chakraborty et al., 2024; Tang et al., 2023; Venado et al., 2025), and paddy systems offer a favourable initial setting given the existing analytical framework for biological nitrogen fixation in that context (Zhang et al., 2026). This is the priority with the longest timescale and the greatest consequence, since it would determine whether nitrogen claims for non-symbiotic inoculants are defensible.

9.6 Adoption Economics and Reporting Infrastructure

Two enabling requirements support all of the above. Farm-level economic analysis across contrasting production systems is needed to establish what performance profile the technology should target, since a conditional benefit and a consistent smaller benefit imply different research strategies, and the existing evidence base is confined to isolated national studies (Chala et al., 2025). Separately, adoption of a minimum reporting set for inoculant studies, specifying enumeration method, storage regime, delivered dose and, where relevant, verified establishment, would make future studies comparable at negligible cost. Consistent reporting of strain identifiers, genome accessions and current nomenclature alongside historical designations would additionally protect the literature against the retrieval and traceability problems created by ongoing taxonomic revision (Gupta et al., 2020). Neither requirement is scientifically demanding, and both are prerequisites for the cumulative synthesis the field currently cannot perform.

10. Conclusions

The mechanistic basis for plant growth promotion by rhizobacteria is established, and the objection to be raised against the field is not that its science is weak but that the strength of evidence differs greatly between mechanisms in ways that reviews and product claims frequently flatten. Pathogen antagonism and immune priming are supported by field evidence generated under regulatory scrutiny. Phosphorus mobilisation is supported by both mechanistic and multi-site agronomic evidence, and the agronomic evidence specifies the condition under which the benefit appears. Hormonal modulation is physiologically well supported and agronomically less so. Volatile signalling and associative nitrogen fixation remain principally supported by controlled-environment work, and in the case of nitrogen the quantitative contribution under agricultural management is genuinely unknown rather than merely imprecise.

The most defensible general conclusion concerns conditionality. Yield benefits from rhizobacterial inoculation are real, moderate in magnitude and dependent on the presence of an environmental constraint that the inoculant mechanism can relieve. This is a robust finding supported by independent quantitative syntheses and consistent with the mechanistic account. It is also the finding with the greatest practical consequence, and the one most often obscured by the presentation of mean effects as though they described a general property of the technology. Conditionality is not a failure of the technology; it is its defining characteristic, and evaluation designs, efficacy claims and extension advice should be constructed around it rather than despite it.

Ecological analysis supplies the most coherent explanation for variable field performance. Introduced strains enter occupied communities, establishment is governed by interaction rather than by intrinsic capability, and populations decline. Whether persistence is necessary for benefit remains unresolved, and the question is answerable with existing methods. It is not answered largely because inoculant density is seldom measured after application, which leaves the central variable of the ecological account unobserved in most published work.

Formulation science has produced real advances in viability preservation across encapsulation, hydrogel and seed-coating platforms. The recurrent weakness is structural rather than technical: viability is treated as the endpoint, and the inference from preserved cells to agronomic benefit is embedded as an assumption in the design of most studies rather than tested by them. Closing that chain within single experimental systems would strengthen the formulation literature more than any additional materials innovation.

Commercialisation constraints deserve treatment as scientific problems rather than as external obstacles. Product quality, regulatory design and adoption economics each generate answerable empirical questions, and each is presently supported by evidence far thinner than that available for mechanism. The demonstration that marketed microbial products may contain little viable declared organism establishes that the concern is substantive, and the absence of comparable verification for bacterial inoculants is a gap that the sector could close inexpensively and has not.

The broader significance of this synthesis lies in the connection between its parts. The field's central difficulty is not any single deficiency but the mismatch between a mechanistic literature operating at high evidential standards and applied, formulation and

commercial literatures operating at lower ones, with inferential steps between them that are assumed rather than demonstrated. Progress requires closing those steps: from trait to causal contribution, from viability to colonisation, from colonisation to yield, and from yield in one environment to specified performance across many. Each is achievable with current methods. Until they are closed, the reasonable position is that plant growth-promoting rhizobacteria are a conditionally valuable component of nutrient and stress management whose benefits are demonstrable under identifiable constraints, and are not a general substitute for mineral fertilisation.

11. Limitations

This review is subject to the limitations intrinsic to narrative synthesis. Source selection was purposive rather than exhaustive, and interpretive judgement determined which studies were treated as decisive for each question. Selection bias and interpretive bias cannot be excluded despite an explicit search strategy, stated eligibility criteria and appraisal of each retained study against design-appropriate criteria. A different reviewer applying the same criteria would produce a different, though probably overlapping, evidence set, and might weight the competing explanations for field variability differently.

Access to subscription databases including Web of Science Core Collection, Scopus and discipline-specific agricultural indexes was not available. Searching was confined to two open scholarly sources, and although these provide broad coverage of the biological literature, agronomic and soil science journals indexed principally in agricultural databases are likely to be under-represented. Field trial reports published in regional agronomic outlets and in national research reports are particularly likely to have been missed, and such reports are disproportionately likely to include the negative or equivocal results whose scarcity is noted in this review. The restriction to English-language publication compounds this, since a substantial body of applied inoculant research is published in Chinese, Portuguese, Spanish and Russian.

The evidence base itself imposes further constraints. Study designs are heterogeneous in unit of analysis, outcome measure and duration to a degree that precludes quantitative synthesis, and this heterogeneity is the reason a narrative approach was adopted rather than an incidental feature of it. Geographical representation is uneven, with controlled-environment work drawn from a wide range of countries but field evaluation concentrated in a smaller number of production systems, which limits the generality of conclusions about field performance. Evidence on long-term effects is scarce; most studies report a single season, and the cumulative consequences of repeated inoculation on soil communities and on crop performance are essentially uncharacterised. Publication bias toward positive results cannot be quantified from the available material but should be assumed to inflate summary impressions of efficacy.

Two further constraints affect specific conclusions. Findings concerning commercial product quality derive principally from an assessment of mycorrhizal rather than bacterial products, and the extrapolation is explicitly flagged as provisional throughout. Regulatory analysis relies on a small number of jurisdiction-specific studies and cannot support general claims about international regulatory practice. Finally, this manuscript reflects the literature accessible up to the stated search date in a field publishing rapidly, and

conclusions concerning emerging areas including synthetic community design and genome-informed selection are correspondingly provisional.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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