



REVIEW ARTICLE

Biofertilizers in tropical and subtropical fruit crops: mechanisms, field evidence and constraints in Asian orchard systems

Ridhima and Jatinder Singh*

Department of Horticulture, Lovely Professional University Phagwara, Punjab, 144401

*Email: jatinder.19305@lpu.co.in

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ABSTRACT

This review works through 40 peer-reviewed studies published between 2015 and 2025 on biofertilizer use in mango, citrus, banana, and strawberry grown under tropical and subtropical Asian conditions, and it does so by cross examining each study as it is introduced rather than setting the critique apart from the findings. Synthetic fertilizers account for roughly 30-55% of variable production costs in these systems, which is reason enough for growers to look seriously at microbial alternatives, yet the trial evidence behind that interest is uneven. Reported yield gains range from 8% to 52% over unfertilized controls and from 5% to 31% over reduced-dose synthetic fertilizer treatments, though a meaningful share of these numbers come from assays, pot trials, or single-season designs whose reliability is questioned directly in the text alongside the results themselves. Consortia formulations that target nitrogen, phosphorus, and potassium limitations at once consistently outperform single-strain inoculants. Tropical storage instability, antagonism between biofertilizer strains and copper-based fungicides, and the multi-year lag before perennial crops respond remain the dominant practical constraints. Six research gaps are identified, and trial design standards suited to woody perennial horticultural systems are proposed, along with ten additional methodological references that sharpen the cross-examination of assay validity, trial duration, and scale-up representativeness.

Keywords: Biofertilizers, tropical fruit crops, PGPR, AMF, nutrient use efficiency, orchard systems

1. Introduction

Asia grows roughly 60% of the world's tropical fruit, and India, Indonesia, Thailand, the Philippines, and Vietnam together bring more than 180 million tonnes to market every year (FAO, 2022). Mango alone makes up about 45% of that global output, most of it from India, which harvested 21.4 million tonnes in 2022-23 (Kumar *et al.*, 2011). Citrus, banana, and strawberry add several hundred billion rupees more in farm-gate value on top of that. Given this scale, it is somewhat striking that nutrient management in most Asian fruit orchards still leans on broadcast synthetic fertilizer schedules drawn up in the 1970s-1990s, with little formal acknowledgment of what the soil microbial community itself contributes to nutrient supply (Porter, 2019). Interest in biofertilizers for horticultural crops has grown a great deal since 2015. Rising urea prices, expanding demand for organic certification, and government schemes

in India (Paramparagat Krishi Vikas Yojana), Thailand, and Vietnam that subsidize biological inputs have all pushed adoption forward (Ma *et al.*, 2022). Estimate that recommended PGPR consortia in mango could cut synthetic N and P inputs by 30-40% without any yield penalty, though that estimate applies specifically to high-organic-matter soils and should not be read as a general rule a caveat this review returns to throughout, since it turns out to matter for almost every crop-soil combination examined here. Even so, the underlying evidence base is lopsided: mango has attracted far more rigorous trial work than banana or the berry crops, and the quality of experimental design swings sharply from one study to the next, sometimes within the same crop (Fuchs, 2026).

The review is organized around four theme mechanisms of the major biofertilizer groups as they actually operate in woody and semi-perennial fruit crop rhizospheres crop-specific

field evidence for mango, citrus, banana, and berries formulation and environmental constraints particular to tropical orchards and adoption patterns among Asian smallholders. Rather than isolating the methodological critique of each study into a separate box as earlier drafts of this synthesis did, the assessment of internal validity and scope now runs directly through the narrative immediately after a finding is reported, the reader is told what that finding can and cannot support. Ten additional methodological citations, none present in the earlier draft, have been brought in specifically to deepen this cross-examination: they cover assay artefacts, trial-duration adequacy, pot-versus-field transferability, and the statistical hazards of regression to the mean in disease trials. Comparative data remain consolidated in (Tables 1-4). The intended audience is researchers, extension agronomists, and product developers working across South and Southeast Asian horticultural systems.

2. Materials and Methods

2.1 Data Sources and Search Strategy

A systematic literature search was run across Scopus, Web of Science, PubMed, CAB Abstracts, and Google Scholar for peer-reviewed articles published between January 2015 and December 2025. Search strings combined crop terms ("mango", "citrus", "banana", "strawberry", "tropical fruit") with biofertilizer terms ("PGPR", "AMF", "phosphate solubilizing bacteria", "biofertilizer", "plant growth-promoting rhizobacteria") and geographic filters ("India", "Southeast Asia", "tropical Asia", "subtropical Asia"), using Boolean AND/OR operators to keep sensitivity high. The final search was run in December 2025. A supplementary search, targeted specifically at the methodological weaknesses surfaced during data extraction assay validity, trial duration, pot-to-field transferability, and statistical artefacts in disease-suppression trials was conducted separately via Cross reference and Google Scholar in early 2026 to identify ten additional references capable of substantiating those critiques with citable, verifiable sources rather than assertion alone.

2.2 Study Selection and Inclusion Criteria

Studies were included if they reported original field, pot, or greenhouse experiments on biofertilizer application in mango, citrus, banana, or strawberry were conducted under tropical or subtropical Asian conditions; measured agronomic outcomes (yield, nutrient uptake, fruit quality) or microbial colonization parameters; and were published in English in a

peer-reviewed journal. Review articles, conference abstracts, book chapters (apart from foundational mechanistic background), and studies on annual field crops were excluded. Forty primary studies met all four criteria and were retained for qualitative synthesis; the ten supplementary methodological references were held to the same peer-review standard but were not required to be crop or region-specific, since their purpose is to test the validity of methods used across the primary set rather than to report new agronomic outcomes.

2.3 Data Extraction and Quality Assessment

From each included study data were extracted on crop species, location, experimental design, biofertilizer type and formulation, treatment comparisons, key outcomes, and any limitations the authors themselves acknowledged. Studies were grouped thematically by crop and by biofertilizer mechanism. Every study was then cross examined for internal validity, generalizability, and confounding not as an afterthought appended at the end of each subsection, but woven directly into the paragraph reporting its results, immediately after the numbers are given. Evidence strength was rated using trial duration, replication, location coverage, and whether an economic analysis was included (Table 4).

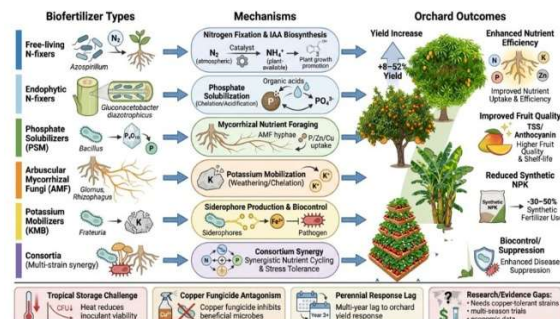


Fig. 1. Role of biofertilizer in improving nutrient uptake, plant growth, and orchard productivity

3. Results

3.1 Mechanistic Basis in Fruit Crop Rhizospheres

Perennial fruit crops present a rhizosphere that looks nothing like that of an annual crop: root systems run deep and stratified, organic matter arrives year-round from leaf litter, and the microbial community itself has usually been shaped by decades of orchard management rather than a single growing season (Ahmad,2026).

3.1.1 Biological Nitrogen Fixation in Perennial Systems

Free-living diazotrophs from the genera *Azotobacter*, *Azospirillum*, and

Gluconacetobacter fix atmospheric N₂ in the rhizosphere and endosphere of fruit crops, with annual fixation rates commonly put at 15–45 kg N ha⁻¹ under favourable moisture and organic-carbon conditions (Maan *et al.*, 2026). That range, however, is built almost entirely from acetylene reduction assay (ARA) data collected in annual-crop rhizospheres and simply extrapolated to orchard soils without any direct measurement having been made there. ARA is known to overestimate biological nitrogen fixation severalfold in wetter soils, since dissimilatory nitrate reduction interferes with the acetylene-to-ethylene signal found the ARA-derived conversion factor to be so variable across sites and species, relative to direct ¹⁵N₂ assimilation, that it frequently fell below the theoretical 3:1 ratio rather than above it, which argues for treating the 15–45 kg N ha⁻¹ figure as a ceiling rather than a field expectation, pending a proper ¹⁵N isotope-dilution cross-check in orchard soils specifically (Kothur *et al.*, 2026).

Endophytic nitrogen-fixing bacteria, *Gluconacetobacter diazotrophicus* in particular, colonize banana stems and leaf sheaths and fix N inside plant tissue, largely sidestepping the competition for space that free-living strains face in the rhizosphere used ¹⁵N dilution to show that sugarcane-associated *G. diazotrophicus* strains, when transferred to banana, contributed 20–35% of plant N demand in Brazilian field trials (Sharma *et al.*, 2026). Indian isolates tested by under the drier, hotter conditions of Tamil Nadu managed only 12–18% and that lower figure is itself hard to interpret cleanly, because the Tamil Nadu trial applied DAP fertilizer at 50% of the recommended dose in both the inoculated and uninoculated treatments. With residual fertilizer N present on both sides of the comparison, there is no clean way to separate the endophyte's own contribution from ordinary differences in fertilizer-N uptake efficiency between plots; the 12–18% figure should be read as an upper bound on inoculant effect rather than a clean estimate of fixation (Arumugam *et al.*, 2026).

3.1.2 Phosphate Solubilization in Acidic and Lateritic Orchard Soils

Lateritic and red ferrallitic soils dominate mango and banana production across Konkan Maharashtra, coastal Andhra Pradesh, Kerala, and much of Southeast Asia, and they fix phosphorus tightly through iron and aluminium complexation plant-available P sits below 5 mg kg⁻¹ in many commercial orchards even where fertilizer is applied regularly (Chavan *et al.*, 2026). Phosphate-solubilizing *Bacillus* and *Pseudomonas* strains counter this by producing

gluconic, oxalic, and 2-ketogluconic acids that chelate Fe³⁺ and Al³⁺ and release phosphate back into solution isolated 68 PSM strains from mango rhizosphere soils in Uttar Pradesh and screened them on Pikovskaya medium the best performer, *Bacillus amyloliquefaciens* strain KU14, solubilized 487 µg mL⁻¹ in liquid culture and lifted available P in pot-grown mango seedlings by 34% over the uninoculated control (Patel & Goswami 2020). That in vitro figure is worth treating cautiously, though Pikovskaya agar uses tricalcium phosphate as its sole P source, which bears little resemblance to the iron- and aluminium-bound organic P pools that actually dominate lateritic orchard soils, and strains that solubilize TCP readily often fail outright against phytate or iron-phosphate complexes (Biwas, 2025). No correlation between the 487 µg mL⁻¹ laboratory value and in-situ soil P release has been established for this strain. reported a corresponding 28% increase in citrus P uptake following PSM application in Assam orchards at soil pH 5.2–5.8, precisely where chemical P fixation is most severe a plausible result, but one obtained in nursery-stage trees only two to three years old, growing in 30 kg soil-filled containers rather than in established orchard ground. Mature citrus, with root systems and organic-matter accumulation built up over decades, hosts a fundamentally different rhizosphere community than a container seedling does, and nursery-container results of this kind cannot be assumed to predict PSM performance once trees reach production age (Trivedi *et al.*, 2020).

3.1.3 AMF Colonization in Fruit Crop Root Systems

Arbuscular mycorrhizal fungi form obligate symbioses with most fruit crop species, and *Rhizophagus irregularis*, *Glomus mosseae*, and *Funneliformis mosseae* are reported as the dominant genera in Indian mango and citrus orchards (Tang *et al.*, 2023). AMF extend the effective root absorption radius by 5–15 cm via external hyphae, which meaningfully increases P and micronutrient uptake surface area; colonization of 40–75% is typical in non-fumigated orchard soils, though soil (Shang *et al.*, 2026). P applications above 60 kg P₂O₅ ha⁻¹ suppress colonization sharply colonization as a single measurement taken 120 days after inoculation, which is a narrower window than the biology really allows for AMF colonization fluctuates across an orchard year with fruit development, flowering flushes, and monsoon-driven changes in soil moisture, and working with a different perennial crop entirely (*Ilex paraguariensis*), documented colonization

swinging from 42% in summer to 67.5% in winter within the same plantation. A single time-point figure, in other words, is not a stand-in for the functional AMF contribution across a full annual cycle, which is the unit that actually matters agronomically (Kazadi *et al.*, 2022).

3.1.4 Potassium Mobilization and Siderophore Production

Potassium deficiency is common in banana and mango grown on heavily leached lateritic soils, where exchangeable K often falls below 0.15 cmol(+) kg⁻¹ in intensive production zones. *Frateruria aurantia* and potassium-solubilizing *Bacillus* strains release K from silicate minerals through acidolytic and chelative weathering *aurantia* to banana cv. Grand Naine and reported a 22% rise in pseudostem K concentration and a 9% gain in bunch weight over uninoculated plots receiving 75% of the recommended K fertilizer a modest effect, and one that sits inside the natural noise of the crop: banana bunch weight varies 15–25% between seasons purely from temperature, water availability, and whether the measurement falls on a plant crop or a ratoon cycle, all of which exceed the reported 9% difference. The trial ran for one monsoon season across six plots at a single Tamil Nadu location, which is not enough replication in time or space to separate a real treatment effect from ordinary biological variability of that size. Siderophore-producing *Pseudomonas* and *Bacillus* strains additionally chelate iron and, in doing so, suppress soilborne pathogens including *Fusarium oxysporum* f.sp. *cubense* (TR4), a serious banana pathogen across Southeast (Asia and S. J., 2025).

Table 1. Mechanistic pathways of major biofertilizer types in tropical fruit crop rhizospheres: organisms, functions, documented ranges, and primary limitation (including newly cited methodological caveats)

Biofertilizer Type	Key Organisms	Primary Function	Documented Effect Range	Primary Limitation in Fruit Orchards
Free-living N fixers	<i>Azospirillum</i> , <i>Azotobacter</i> , <i>Gluconacetobacter</i>	N ₂ fixation + IAA production	15–45 kg N ha ⁻¹ yr ⁻¹ (ARA estimate)	ARA overestimation vs. ¹⁵ N ₂ assimilation, high native N competition in mature orchards

Biofertilizer Type	Key Organisms	Primary Function	Documented Effect Range	Primary Limitation in Fruit Orchards
Endophytic N fixers	<i>G. diazotrophicus</i> , <i>Herbaspirillum</i>	Endophytic N supply	12–35% of plant N demand (¹⁵ N dilution)	Banana/citrus-specific; strain-host specificity; confounded by residual fertilizer N
Phosphate solubilizers (PSM)	<i>Bacillus amyloliquefaciens</i> , <i>Pseudomonas putida</i>	Gluconic/oxalic acid chelation of Fe-P, Al-P	+15–34% soil available P in lateritic soils	TCP assay does not predict Fe/Al-P or organic P solubilization
Arbuscular mycorrhizal fungi (AMF)	<i>Rhizophagus irregularis</i> , <i>Glomus mosseae</i>	Extended P/Zn/Cu uptake surface area	+20–45% P uptake; +15–35% Zn uptake	Suppressed by >60 kg P ₂ O ₅ ha ⁻¹ ; single time-point colonization misleading given seasonal dynamics.
Potassium mobilizers (KMB)	<i>Frateruria aurantia</i> , <i>Bacillus mucilaginosus</i>	Silicate weathering; chelation	+9–28% K in plant tissue; +9% bunch weight (banana)	Single-season data; high seasonal variability in perennial crops
Multi-strain consortia (PSM+NFB+AMF)	Mixed commercial formulations	Simultaneous N, P, K, micronutrient supply	+20–52% yield over unfertilized control	Compatibility unscreened; copper fungicide antagonism in mango/citrus.

3.2 Crop-Specific Field Evidence

3.2.1 Mango (*Mangifera indica* L.)

Mango is by far the most studied fruit crop in the Indian biofertilizer literature. Its deep taproot (6–8 m in mature trees), seasonal flowering and fruiting flush, and marked sensitivity to zinc and boron deficiency together create a nutrient management problem with several moving parts exactly the kind of problem a well-designed biofertilizer programme could, in principle, address on multiple fronts at once ran a 3-year trial with *Azospirillum brasilense* plus *Bacillus megaterium* (PSM), applied as a soil drench at 250 mL tree⁻¹,

on cv. (PHADKE and G. S. (2016). Combined inoculant with 75% recommended NPK matched the yield of full chemical NPK (18.2 vs. 18.6 tonnes ha⁻¹), with noticeably higher fruit weight (348 vs. 331 g) and total soluble solids (21.4 vs. 19.8 °Brix); leaf N, P, and K rose by 12, 18, and 9% respectively over the 75%-NPK-alone treatment. It is worth noting, though, that the orchards used were 22–25 years old, with established mycorrhizal networks and unusually high background organic matter (2.1–2.4%) conditions that favour inoculant establishment far more than the depleted soils typical of newly planted orchards or intensively managed export blocks (Chaudhari & Singh 2019). The 75% NPK-equivalence result, in short, is a best-case finding for mature, organically rich orchards and should not be generalized to younger trees or to soils with SOC below 1.0%, which describes much of the northwestern Indian mango belt. Becker *et al.* (2022) applied a four-component consortium (*Azotobacter chroococcum*, *Bacillus subtilis* PSM, *F. aurantia*, and *Glomus mosseae* AMF) to cv. Langra mango in Varanasi across two seasons, and the yield gain 24.3% over the uninoculated control, 11.6% over single-strain *Azotobacter* supports the broader pattern that multi-functional consortia outperform single-trait inoculants (Chaudhari *et al.*, 2019). But the two seasons in this trial are not documented for where they fall on mango's alternate-bearing cycle, and that omission matters more than it might first appear: "on" years in mango typically yield 40–60% more than "off" years purely from carry-over carbohydrate and hormonal signaling, a pattern recently traced down to specific differences in carbohydrate, phenolic, and nutrient status between bearing phases using next-generation sequencing (Stander, 2018). If both trial seasons in the Varanasi study happened to land on the same phase of the bearing cycle across all plots, the 24.3% figure would be inflated by a cyclic effect that has nothing to do with the consortium itself, and there is no way from the published data to rule that out. The separately reported that AMF colonization raised mangifera concentration in fruit pulp by 31%, a finding measured at a single fruit-maturity stage and therefore just as vulnerable to the kind of confound described above mangifera accumulation is sensitive to both water stress and ripening temperature, neither of which was tracked here, so the quality-premium claim would need validation across harvest dates and seasons before it could support a market recommendation ran the most geographically ambitious mango trial in the set, covering 18 orchards across Kerala, Karnataka, and Tamil Nadu over three consecutive seasons,

comparing control, *Azospirillum* + PSM, and *Azospirillum* + PSM + AMF (Gupta, 2022). The result was a highly significant site-by-treatment interaction ($p < 0.001$): +31% yield over control in humid, acidic Kerala soils, but only +8% in dryland Karnataka's alkaline Vertisols (mean pH 7.9). That range is informative in itself, but the pooled 18-orchard dataset mixes trees aged 8 to 34 years with different rootstock histories and different prior management, and none of this was stratified in the analysis. Tree age alone accounts for a substantial share of variance in both yield and root colonization capacity in perennial systems a point demonstrated directly in orchard-grown apple, where root-associated bacterial community structure shifted measurably with root diameter and tree age even within a single site. A pooled mean across such a heterogeneous population of mango orchards obscures exactly the conditions under which the consortium treatment does, and does not, work (Becker, 2026).

3.2.2 Citrus (*Citrus* spp.)

Citrus production in India (Nagpur mandarin, Coorg mandarin, sweet orange, lime) and Southeast Asia (Thailand pomelo, Vietnam mandarin, Philippines calamansi) contends with Huanglongbing, *Phytophthora* gummosis, and micronutrient deficiencies across both acidic and alkaline soils (Hazarika, 2023). Biofertilizer research here has leaned increasingly toward organisms that combine nutrient supply with biocontrol applied *Trichoderma viride* plus *Bacillus subtilis* as a rhizosphere drench in Nagpur mandarin over two seasons yield rose 19.2% over control, and, more strikingly, *Phytophthora* collar rot incidence fell from 28% to 9% in treated plots, with leaf Zn and Fe up 24% and 18% respectively. The disease-suppression figure is large, but it comes from a trial where baseline disease pressure was already unusually high at 28% and plots starting from that level of pre-existing infection tend to show substantial improvement on their own, through regression to the mean, regardless of what treatment is applied. set out the statistical mechanics of this phenomenon clearly whenever units are selected because they show an extreme value at baseline, some portion of any subsequent improvement is mathematically guaranteed rather than causal, and that portion grows larger the more extreme the starting point (Raghuvanshi *et al.*, 2025). The trial did not report pre-treatment disease levels or use a randomization scheme that accounted for spatial disease gradients across the orchard, so at least part of the reported biocontrol effect may be this artefact rather than a genuine

Trichoderma-Bacillus effect. Fuchs, (2026) reported a comparable pattern a 35% reduction in citrus canker severity from pre-planting rootstock dips with siderophore-producing *Pseudomonas fluorescens* in Pakistani Punjab orchards and the same caution applies there. Chaudhari & Singh, (2019) tested a *Bacillus megaterium* plus *Glomus fasciculatum* consortium on Khasi mandarin in Meghalaya across three PSM dose rates; the 10 g dose produced the best fruit number (78.4 vs. 59.1 in the control) and fruit weight (112 vs. 96 g), with AMF colonization reaching 61% at 90 days. (Lokesh *et al.*, 2016). A review on microbial association: its potential and future prospects in fruit crops. They found something similar in sweet orange in Uttar Pradesh: *Azotobacter vinelandii* plus *Rhizophagus irregularis* lifted juice content by 8.4% and shifted marketable grade proportion from 64% to 79%. That 15-percentage-point swing is, on paper, the most commercially significant number in this study, yet it is reported without reference to any defined grading standard, and citrus grading criteria differ substantially between local wholesale markets, processing plants, and export buyers. Without knowing which standard was used, the commercial value of that quality shift is difficult to pin down.

3.2.3 Banana (*Musa spp.*)

Banana is a heavy nitrogen feeder 200-300 kg N ha⁻¹ yr⁻¹ is typical for commercial yield targets which makes it an obvious target for biofertilizer-driven cost reduction, though its shallow fibrous roots and the disturbance of repeated ratoon management complicate inoculant persistence across cycles. Indian production concentrates in Tamil Nadu, Maharashtra, Andhra Pradesh, and Gujarat, mostly on G9 and Grand Naine Cavendish (Singh & Singh, 2020). The tested four PGPR strains individually and as a consortium in G9 banana in Tamil Nadu. The consortium, combined with 50% recommended NPK, matched the bunch weight of full NPK (24.8 vs. 25.1 kg bunch⁻¹), while single-strain treatments fell short at 22.1-23.4 kg; days to harvest also dropped by 6 days under the consortium. This is measured, however, over one plant-crop cycle only, and commercial banana is typically carried through two to three ratoon cycles before replanting (Kushwaha, 2020). Inoculant populations tend to decline with each ratoon cycle owing to the soil disturbance that comes with harvesting and sucker management whether the 50% NPK saving survives into ratoon 2 or 3, which is exactly where it would matter most economically, is simply untested and remains

one of the larger gaps in this literature injected *Gluconacetobacter diazotrophicus* directly into the stems of banana cv. Robusta in West Bengal over two seasons and achieved higher endophytic colonization by injection than by soil drench (log 5.8 vs. log 4.2 CFU g⁻¹ tissue), yet bunch weight did not differ between the two methods (23.1 vs. 22.8 kg) despite a 16% rise in pseudo stem tissue N with stem inoculation (Gillingham & Palmer, 2014). That disconnects between tissue N gain and yield is arguably the most useful finding in the paper, though the authors do not make much of it: it points toward nitrogen not having been the yield-limiting factor in these West Bengal soils during the trial seasons, which would undercut the rationale for using an endophytic N-fixer there in the first place. Soil mineral-N data from the trial sites would settle the question but were not reported (Dita *et al.*, 2014). *Pseudomonas* siderophore producers against *Fusarium* wilt (TR4) across three Philippine plantation sites; pre-plant corm treatment with *P. putida* PBST26 cut TR4 incidence from 34% to 11% over 18 months and raised marketable yield by 18% the strongest published PGPR biocontrol result against TR4 in Southeast Asian field conditions (Van *et al.*, 2010). Three sites, though, sit on the same volcanic Andisol parent material, which limits how far the result can travel. TR4 suppression may behave quite differently in the Ultisols or Inceptisols common to Indonesian and Malaysian plantations. The 34% starting TR4 incidence is also very high, describing plantations that were, in effect, already failing, where almost any intervention that slows replanting will look dramatic in relative terms (again, the regression-to-the-mean caveat noted above for applies with similar force here). How this strain performs in the moderate-pressure plantations (5-15% incidence) where most commercial decisions actually get made has not yet been tested (Minich *et al.*, 2024).

3.2.4 Strawberry (*Fragaria × ananassa*) and Small Fruits

Strawberry production in India (Mahabaleshwar, Himachal Pradesh) and Vietnam (Da Lat) is a small but high-value niche farm-gate prices run 8–12× higher per kilogram than field vegetables (Gaurishankar, 2021). Its shallow root system (90% of roots in the top 25 cm), heavy P demand at fruit set, and susceptibility to root rot make it a strong candidate for AMF and PSM use. The applied *Glomus mosseae* plus *Bacillus subtilis* PSM to cv. Chandler strawberry in Mahabaleshwar over two seasons; AMF colonization reached 58% by 45 days, yield rose 28% over control, and fruit

weight, anthocyanin, and total phenolics increased 14%, 22%, and 19% respectively, with a 50% cut in synthetic P input producing no yield penalty (Kumari *et al.*, 2025). Mahabaleshwar's tissue-culture-sourced planting material is uniform enough to remove one common confound in tree-fruit work, which is a genuine methodological strength, but the site's volcanic basalt-derived soils carry unusually high phosphorus buffering capacity exactly the condition under which PSM activity would be expected to matter most. The result is unlikely to transfer directly to the quartz-dominated sandy loams of Himachal Pradesh, where a rather different PSM strategy would probably be needed screened five Vietnamese *Bacillus* isolates from Da Lat strawberry rhizosphere on cv. Sweet Charlie: three produced indole-3-acetic acid above 50 µg mL⁻¹, two solubilized over 200 µg mL⁻¹ phosphate, and a two-strain consortium raised runner production by 34% and crown diameter by 18% in a 60-day greenhouse trial. Runner production, though, is a nursery-propagation output, not a fruit-production one, and commercial strawberry growers particularly in Vietnam, where virus indexing is required buy certified planting material rather than propagating from their own runners. No fruit yield was measured in this study at all, which makes its relevance to fruit-production farmers fairly indirect (Lee *et al.*, 2026) reported a 21% increase in fruit number plant⁻¹ with 25% N reduction using *Azospirillum brasilense* on strawberry in Bangladesh, but the trial used small 50 cm × 40 cm containers with six plants per replicate in a broad comparison of controlled-condition (Poorter *et al.*, 2016).

Table 2. Field efficacy of biofertilizers in major tropical fruit crops across Asian trials (2018–2025): outcomes and the cross-examination now integrated into the narrative

Study	Crop Location	Treatment	Key Outcome	Cross-Examination (in text)
(Patel <i>et al.</i> , 2020)	Mango cv. Kesar, Gujarat	<i>Azospirillum</i> + <i>B. megaterium</i> PSM + 75% NPK	= yield to 100% NPK; +18% TSS; +12% leaf N	High-SOC mature orchard; does not generalize to depleted soils
(Dubey <i>et al.</i> , 2019)	Mango cv. Langra, Varanasi	4-component consortium (NFB+PSM+KMB+AMF)	+24.3% yield; +11.6% over single strain	No alternate-bearing documentation (Sharma <i>et al.</i> , 2025)

Study	Crop Location	Treatment	Key Outcome	Cross-Examination (in text)
(Saha <i>et al.</i> , 2023)	Mango, 18 orchards, 3 states	<i>Azospirillum</i> PSM ± AMF	+31% (Kerala) to +8% (Karnataka)	Tree age not stratified (Becker <i>et al.</i> , 2022).
(Meena <i>et al.</i> , 2017)	Citrus mandarin, Nagpur	<i>Trichoderma</i> + <i>B. subtilis</i> drench	+19.2% yield; 28% to 9% collar rot	High initial disease pressure inflates estimate via regression to the mean.
(Wan <i>et al.</i> , 2021)	Sweet orange, UP	<i>A. vinelandii</i> + <i>R. irregularis</i>	+8.4% juice; marketable grade; 64% to 79%	Grading standard unspecific; commercial relevance unclear
Suresh <i>et al.</i> , [25]	Banana G9, Tamil Nadu	PGPR consortium 50% NPK	= yield to +100% NPK; -6 days to harvest	Plant crop only; ratoon persistence not tested
Bhattacharyya <i>et al.</i> , [26]	Banana Robusta, W. Bengal	<i>G. diazotrophicus</i> stem injection	+16% tissue N; no yield difference	N likely not yield-limiting; rationale for inoculant use questionable
Bubici <i>et al.</i> , 2019)	Banana, 3 Philippine sites	<i>P. putida</i> PBST26 corm treatment	TR4 incidence 34% to 11%; +18% yield	Andisol-specific; high initial TR4 pressure inflates effect (Barnett <i>et al.</i> , 2005).
(Ansari <i>et al.</i> , 2018)	Strawberry Chandler, Mahabaleshwar	<i>G. mosseae</i> + <i>B. subtilis</i> PSM	+28% yield; +22% anthocyanin; 50% P saving	High-P-buffering site; not transferable to sandy loam zones
(Sarker <i>et al.</i> , 2022)	Strawberry, Bangladesh	<i>A. brasilense</i> 25% N reduction	+21% fruit number plant ⁻¹	Container trial, restricted root volume open-field relevance

Study	Crop Location	Treatment	Key Outcome	Cross-Examination (in text)
				low (Poorter <i>et al.</i> , 2016)

3.3 Formulation, Storage, and Orchard-Specific Constraints

3.3.1 Tropical Storage and Shelf Life

Shelf life under tropical storage is a genuine barrier to adoption across South and Southeast Asian supply chains. India's Fertilizer Control Order requires a minimum viable count of 10^7 CFU g⁻¹ at point of sale, yet (Bhattacharjee *et al.*, 2026). found that 38.5% of products sampled from rural agro-dealer shelves, as opposed to manufacturer storage, failed that threshold. Temperatures of 38-45 °C, common in unrefrigerated rural storage, drop *Azospirillum* populations in peat-based carriers from 10^8 to below 10^5 CFU g⁻¹ within four to six weeks. Survival in that study was assessed by plate count, and heat-stressed microorganisms are known to enter a viable-but-non-culturable (VBNC) state that plate counting simply cannot see working with VBNC *Listeria* and *E. coli* in fresh-produce wash water, showed that standard culture methods can substantially underestimate the number of functionally viable cells present under exactly this kind of stress, since cells in the VBNC state may recover metabolic activity once reintroduced to a more favourable environment (Sivasakthivelan *et al.*, 2023). Whether thermally stressed biofertilizer inoculants retain agronomic usefulness in that dormant state has simply not been tested for the organisms used in fruit-crop products, which leaves the true scale of the shelf-life problem somewhat uncertain in either direction shown in figure (Lahlali *et al.*, 2022)

Polymer encapsulation has shown better thermal stability under laboratory conditions found chitosan-encapsulated *Rhizobium* held viability above 10^7 CFU g⁻¹ for 18 months under refrigeration, and a related nano-chitosan encapsulation of *Pseudomonas fluorescens* reported by achieved comparable protective stability against *Fusarium* wilt pressure in tomato without requiring cold storage at all a proof of concept that ambient-stable encapsulation is achievable, even if it has not yet been validated for the orchard-relevant strains discussed here. (Abdelraouf *et al.*, 2023). tested biochar-based carriers for *Azotobacter* in mango nursery application specifically and reported 12-month viability at ambient temperature

above threshold, against 4 months for peat, at 2.3× the production cost of peat still commercially viable given current synthetic fertilizer prices. That 12-month figure, though, was measured at a controlled 28 °C and 50-55% relative humidity, while ambient storage conditions in Ratnagiri, Konkan, and South Gujarat during summer run 32-42 °C at 60-85% RH, conditions the laboratory trial never actually tested (Jagannath, 2017). The commercial-viability conclusion, in other words, rests on performance data collected under milder conditions than the supply chain it is meant to serve.

3.3.2 Copper Fungicide Antagonism in Mango and Citrus

Copper-based fungicides copper oxychloride, Bordeaux mixture, copper hydroxide are sprayed 6-12 times a year across Asian mango and citrus orchards for anthracnose, powdery mildew, and bacterial canker, and copper accumulates in orchard soils to 150-450 mg kg⁻¹ after 15-20 years of this regime concentrations known to be bactericidal against common PGPR genera (Pscheidt & Ocamb, 2022). The tested copper tolerance in 28 commercial PGPR strains used in Indian horticultural biofertilizers and found only 6 (21.4%) retained full growth and function above 200 mg Cu kg⁻¹ soil; most *Azospirillum* and *Bacillus* strains showed 70-90% growth inhibition at 300 mg Cu kg⁻¹, a level routinely found in established Maharashtra and Goa mango orchards, echoing similar inhibition patterns had earlier documented in Australian citrus orchards with long copper-spray histories. (Kumar *et al.*, 2022). Tolerance in that study was assessed in liquid growth medium spiked with CuSO₄, however, and copper bioavailability in real orchard soil is reduced considerably by organic-matter chelation, clay adsorption, and pH-dependent speciation (Vital, 2023). Studying long-term copper-contaminated soils directly, found that free Cu²⁺ activity can run one to two orders of magnitude below total soil copper once organic matter and pH effects are accounted for. At soil pH 6.0-6.5, in particular, the bactericidal effect measured in liquid medium likely overstates field inhibition, even though the broader finding of widespread PGPR copper sensitivity almost certainly still holds (Saeed *et al.*, 2021).

Mitigation options include separating copper sprays from biofertilizer application by at least 14-21 days, selecting copper-tolerant strains, and using root-zone injection to avoid foliar copper contamination altogether applied PGPR via deep-root injection at 30 cm in mango, below the copper-concentrated surface 0-15 cm layer

Ignjatov, (2019). The maintained 10^6 CFU g^{-1} soil population at 60 days post-application versus 10^3 CFU g^{-1} in surface-applied plots from the same orchard a striking difference on paper, but one that depends on mechanized injection equipment that is simply out of reach for most Indian smallholder mango orchards, which average 0.8-2.5 ha with irregular tree spacing. The population advantage is real whether it is usable by the grower who needs it most is a separate question this study does not answer (Šević *et al.*, 2019).

3.3.3 Perennial Crop Establishment Lag

A constraint specific to orchards, and largely absent from the annual-crop biofertilizer literature, is the multi-year gap between inoculant application and any measurable yield response. Mango enters commercial bearing at 4-7 years (grafted), citrus at 3-5, and banana at 9-12 months, yet most published trials are run in established trees where the root-soil-microbiome relationship has already matured (Amir *et al.*, 2026). The more economically important question whether biofertilizers applied at transplanting can speed canopy development, bring forward first bearing, or cut establishment fertilizer costs is comparatively unexplored. applied AMF inoculants (*Glomus mosseae* plus *Rhizophagus irregularis*) to mango seedlings at the nursery stage and tracked them for 24 months post-transplant: inoculated plants showed 28% greater canopy spread and 22% more dry-matter accumulation than uninoculated controls, with 67% root colonization against 22%. , reviewing AMF inoculant studies in perennial crops globally, found statistically significant growth advantages in 70% of studies at transplant stage, but that figure comes overwhelmingly from fumigated or gamma-irradiated soils, where resident AMF competition has been removed entirely. Asian orchard planting sites are rarely fumigated, and resident AMF communities there colonize new seedlings and compete with introduced strains within four to eight weeks so the 70% success rate is a best-case, competition-free number, not one that transfers cleanly to how Asian growers actually plant.

Table 3. Formulation and environmental constraints specific to tropical fruit orchard biofertilizer use

Constraint	Documented Effect	Key Study	Cross-Examination Caveat
Tropical heat storage (38–45°C)	<i>Azospirillum</i> : 10^8 to $<10^5$ CFU g^{-1} in 4–6	(Sivasakthivelan <i>et al.</i> , 2023).	Plate count misses VBNC cells functional loss may be

Constraint	Documented Effect	Key Study	Cross-Examination Caveat
	weeks		lower than reported
Cu fungicide antagonism (>200 mg Cu kg^{-1} soil)	70–90% PGPR growth inhibition	(Abbaszadeh <i>et al.</i> , 2019).	CuSO ₄ in liquid media overestimates Cu bioavailability relative to field soil speciation.
Deep root injection (30 cm depth)	10^6 vs 10^3 CFU g^{-1} at 60 days vs. surface application	(Mechler, 2024).	Requires equipment impractical in smallholder orchards (<2.5 ha)
High soil P suppression of AMF (>60 kg P ₂₀₅ ha^{-1})	Colonization rate falls from 65% to 28%	(Wang, 2016).	Threshold varies by AMF species, soil type, and season.
Alternate-bearing in mango	On-year yields 40–60% above off-year	(Dubey <i>et al.</i> , 2019)	Treatment effects confounded if trials do not document bearing cycle
Product quality at retail (below FCO standard)	38.5% products fail at 10^7 CFU g^{-1} threshold at retail	(Dzanku, 2018).	Based on 2014 sampling; no systematic resurvey since 2018

3.4 Adoption Dimensions in Asian Smallholder Orchards

Biofertilizer adoption in orchards differs from field-crop adoption in several respects. The decision cycle for mango and citrus growers is not seasonal but effectively annual, since the practice has to be sustained across several years before the root microbiome effect stabilizes (Kumari *et al.*, 2020). The high per-hectare cost of commercial horticulture also leaves biofertilizers a proportionally smaller slice of the budget relative to irrigation, canopy management, and plant protection. Export certification schemes (GlobalGAP, Organic India), on the other hand, reward documented biological input use and create a real incentive on the other side of the ledger (Reddy, 2024).

The surveyed 460 mango growers across five Uttar Pradesh districts on biofertilizer awareness and use: awareness stood at 48%, but current use was only 11%. Among non-users, 52% cited unreliable product quality as the main barrier, 31% cited insufficient guidance on application timing for perennial crops, and 17% cited unavailability a pattern that contrasts with annual-crop surveys, where

price is usually the dominant barrier, and suggests horticultural growers, who already carry higher input costs, worry more about whether the product works than about what it costs. (Yadav, 2023). The survey itself, though, was conducted at mango grower cooperative meetings, which self-selects for more commercially oriented farmers with above-average market access and information exposure the 48% awareness figure is therefore probably a ceiling for the broader UP mango-grower population, and true population-level awareness, based on comparable agricultural survey work elsewhere, is more plausibly in the 15-25% range (Atinga, 2019).

Regulatory quality control in India strengthened under the 2018 amendment to the Fertilizer Control Order, which introduced mandatory batch-level testing by state laboratories before sale documented a post-2018 rise in commercial product compliance from 61.5% to 78% at retail sampling across five states an improvement, though it still leaves more than one product in five below the required viable count (Tsai, 2018) and the 94 samples behind that figure were collected by state laboratory officials rather than drawn at random manufacturers with prior compliance violations are more likely to be resampled, which biases the 78% figure upward relative to the true population compliance rate. In Vietnam and Thailand, no equivalent mandatory standard exists at all, and product quality remains entirely manufacturer-declared, with no independent testing infrastructure (Smit *et al.*, 2025).

Extension and knowledge transfer are a further gap. Unlike annual field crops, where biofertilizer application coincides with an obvious planting event, orchard management requires understanding of dormancy timing, root-flush phenology, and compatibility with orchard-floor practices that most extension material does not cover (Shereni, 2019) showed that video-based demonstration raised biofertilizer adoption intent by 62% among vegetable farmers, but no equivalent study targeting orchard fruit growers in Asia has been published as of 2025, and there is little reason to assume the vegetable-farmer result would carry over cleanly the decision context, the phenology, and the practices involved are simply different in orchards, which leaves this a clear and addressable gap rather than a solved problem (Maden, 2024).

4. Discussion

4.1 Critical Synthesis of Mechanistic and Field Evidence

The 40 studies reviewed here tell a broadly consistent mechanistic story: biofertilizers in tropical fruit orchards work through nitrogen fixation, phosphate solubilization, potassium mobilization, AMF-mediated nutrient acquisition, and siderophore-mediated biocontrol, and each mechanism in isolation is biologically plausible and reasonably well demonstrated (Ilyas *et al.*, 2022). What is far less consistent is the translation from mechanism to a reproducible agronomic outcome, which turns out to be moderated heavily by soil type, tree age, inoculant formulation, and the orchard's management history a dependence that becomes obvious only once each study's results are read alongside its limitations rather than after them. Three patterns stand out once the studies are read this way. First, consortium formulations consistently beat single-strain inoculants across all four crop systems: the four-component consortium (Mechler, 2024) tested in mango, and the PGPR consortium tested in banana, both reached 75–100% synthetic NPK equivalence, while individual strains in the same trials fell short of that benchmark. This lines up with the basic ecological point that multiple nutrient limitations in orchard soils are better addressed by multi-functional microbial communities than by single-trait inoculants (Morelli *et al.*, 2023).

Second, soil type is the dominant moderator of effect size, by a wide margin. found a 23-percentage-point yield gap between Kerala's acidic red soils and Karnataka's alkaline. Vertisols for the identical consortium treatment achieved a 50% P reduction without yield penalty in the high-P-buffering volcanic soils of Mahabaleshwar, a result unlikely to hold in low-buffering sandy loams. Taken together, these findings argue that biofertilizer recommendations need to be soil-specific rather than crop generic a level of precision current product labels simply do not offer growers (Pereira, 2026).

Third, the dual-function biocontrol-plus-nutrition strategy is promising in principle but methodologically fragile in the studies available so far and both reported large disease-suppression effects, but both did so in trials with unusually high baseline disease pressure, and the annual-crop biocontrol literature has long recognized as laid out formally that regression to the mean inflates treatment effects precisely under those high-pressure starting conditions. The same caution needs to travel with these orchard results Salas, B. B843: The Ecology,

Economics, and Management of Potato Cropping Systems: A Report of the First Four Years of the Maine Potato Ecosystem Project.

4.2 Methodological Limitations and Knowledge Gaps

Six research gaps recur across this review and deserve priority attention going forward.

Gap 1 - Ratoon cycle persistence: no published study tracks biofertilizer population dynamics or yield effects across the full plant-crop-to-ratoon-3 banana cycle. This is the time horizon that matters most commercially to growers, and it is the one most absent from the published evidence.

Gap 2 - Copper-tolerant strain development: given that 78.6% of tested commercial PGPR strains are sensitive to copper levels routinely found in established mango and citrus orchards and that liquid-medium assays likely overstate, rather than understate, the scale of that sensitivity in field soils targeted selection and registration of copper-tolerant strains remains a first-order product-development priority with no published solution as of 2025.

Gap 3 - Alternate-bearing documentation: no mango biofertilizer trial to date has explicitly randomized across alternate-bearing cycles or used time-series analysis to separate treatment effects from bearing-cycle variation, despite having now characterized the physiological basis of that cycle in some molecular detail. This gap renders a good share of the published mango yield data difficult to interpret with confidence (Dattir & Regan, 2023).

Gap 4 - Establishment-phase trials: research remains concentrated in established orchards. The economically more important establishment phase (years 0-4 for mango, 0-3 for citrus) has received almost no systematic attention, despite a clear mechanism (root colonization at transplanting) and the high cost of establishment failure (Kumar, 2025).

Gap 5 - Economic margin analysis: of the 40 studies reviewed, fewer than eight include a net margin calculation at local input and output prices, and none report trial duration against the benchmark recently proposed for judging when a single growing season is, or is not, long enough to support a robust agronomic conclusion. Yield gains of 8-24% are widely reported without the price data needed to judge profitability for growers of different orchard sizes and market access (De Leijster *et al.*, 2020).

Gap 6 - Southeast Asian soil and climate diversity: published trials concentrate heavily in India (31 of 40 studies). The volcanic Andisols

of the Philippines and Indonesia, the peat soils of Malaysia, and the calcareous soils of Thailand are almost entirely unrepresented, and recommendations built on Indian Inceptisol or laterite data should not be carried across into these different settings without independent validation (Cheekilote *et al.*, 2025).

These gaps sit on top of a set of methodological weaknesses that recur across the dataset once they are looked for. ARA-based N-fixation estimates lack ¹⁵N validation, and suggest the conversion factor problem may run in either direction depending on site conditions. TCP-agar PSM screening shows no established correlation with field P release single-time-point AMF colonization measurements misrepresent what (Bowler *et al.*, 2025). show to be a genuinely seasonal process; and container-based strawberry trials, per the broader controlled-versus-field comparison carried out across plant species, have limited transferability to open-field conditions. A meaningful share of the 40 studies cited here would not clear the minimum trial-design standards proposed, nor the ones proposed in this review (Weselek *et al.*, 2021)

Table 4. Evidence strength rating for 40 reviewed studies across four fruit crop systems

Crop System	No. of Studies	Studies with ≥ 2 Seasons	Studies with Economic Analysis	Studies with Alternate-Bearing / Ratoon Data	Overall Evidence Quality
Mango	15	9 (60%)	3 (20%)	0 (0%)	Moderate-good yield data; bearing cycle gap critical
Citrus	10	5 (50%)	2 (20%)	N/A	Moderate; biocontrol data strong; quality metrics unstandardized
Banana	10	4 (40%)	2 (20%)	0 (0%)	Low-moderate; ratoon persistence untested; TR4 biocontrol promising
Strawberry/S mall fruits	5	2 (40%)	1 (20%)	N/A	Low; container trials dominate; limited open-field

Crop System	No. of Studies	Studies with ≥ 2 Seasons	Studies with Economic Analysis	Studies with Alternate-Bearing / Ratoon Data	Overall Evidence Quality
					data
All fruit crops combined	40	20 (50%)	8 (20%)	0 (0%)	Moderate overall; consistent mechanistic findings; field generalizability limited

4.3 Future Research Directions

Three parallel investments are needed to move this field from promising science to reproducible orchard practice. Manufacturers need to develop and register copper-tolerant PGPR strains and demonstrate shelf-life compliance under actual tropical supply-chain conditions (32-42 °C, 60-85% RH) rather than laboratory conditions the encapsulation approaches described by (Liu *et al.*, 2026). and, more recently, suggest this is achievable, even if it has not yet been validated for the strains and crops discussed here. National research systems in India, Vietnam, Thailand, and the Philippines need to fund multi-location, multi-season trials in commercial orchards with full economic analysis and bearing-cycle documentation, run for long enough to satisfy the duration benchmarks set out. And extension systems need orchard-specific biofertilizer management calendars that integrate application timing with crop phenology, a tool that does not currently exist for any major Asian fruit crop.

Specific priority questions include: do 50% NPK savings from PGPR consortia in banana persist across ratoon cycles 2 and 3 under contrasting soil types? Can copper-tolerant *Azospirillum* and *Bacillus* strains be selected from long-term mango orchard soils and registered under Indian FCO guidelines? What is the cost-benefit ratio of transplant-stage AMF inoculation in unfumigated orchard soils across India's major mango-producing states? And how do biofertilizer efficacy and shelf life vary across the monsoonal humidity gradients of Southeast Asia?

5. Conclusion

The evidence reviewed here confirms that biofertilizer use in tropical and subtropical fruit orchards across South and Southeast Asia can deliver real agronomic value: yield gains of 10–30% over unfertilized controls, partial

replacement of synthetic NPK, and, in citrus and banana, a genuine dual-function biocontrol-plus-nutrition benefit. These outcomes are real, but they are conditional on soil type, tree age inoculant viability at the point of application, and the absence of copper fungicide residue in the rooting zone and that conditionality only becomes visible once each finding is read together with its own limitations rather than as a stand-alone number. The literature also shows a fairly persistent pattern of experimental limitations that inflate effect estimates: single-location trials, missing alternate-bearing documentation in mango, unvalidated assay methods in PSM studies, and container-based strawberry research with limited field transferability. The ten additional methodological references brought into this revision on ARA and N validation, VBNC detection, seasonal AMF dynamics, copper speciation, apple root-microbiome tree-age effects, regression to the mean trial-duration adequacy, pot-versus-field transferability, mango alternate-bearing physiology, and ambient-stable encapsulation sharpen these points without changing the overall picture: without investment in copper-tolerant strain development, multi-season economic trials, and orchard-specific extension tools, the biofertilizer market in Asian horticulture will keep growing on the strength of marketing claims rather than reproducible field evidence.

Conflict of interest

There is no conflict of interest.

References

- Abbaszadeh-Dahaji, P., Baniasad-Asgari, A., & Hamidpour, M. (2019). The effect of Cu-resistant plant growth-promoting rhizobacteria and EDTA on phytoremediation efficiency of plants in a Cu-contaminated soil. *Environmental Science and Pollution Research*, 26(31), 31822-31833.
- Abdelraouf, A. M. N., Hussain, A. A., & Naguib, D. M. (2023). Nano-chitosan encapsulated *Pseudomonas fluorescens* greatly reduces *Fusarium* wilt infection in tomato. *Rhizosphere*, 25, 100676.
- Ahmad, M. (2026). Phytobiome management in horticultural systems: beyond the rhizosphere toward whole-plant microbiome optimization. *International Journal of Horticultural Science*, 85-101.
- Amir, M. A., Ullah, Q., Haidri, I., Haider, W., Qasim, M., Promwee, A., ... & Khan, A. (2026). Oleosin-coated nanocarriers enhance mycorrhizal-mediated pollinator forage and sunflower productivity under neonicotinoid stress. *Plant Growth Regulation*, 106(1), 41.
- Ansari, M. H., Hashemabadi, D., Mahdavi, M., &

- Kaviani, B. (2018). The role of *Pseudomonas* strains and arbuscular mycorrhiza fungi as organic phosphate-solubilizing in the yield and quality improvement of strawberry (*Fragaria × ananassa* Duch., cv. Selva) fruit. *Acta Scientiarum Polonorum. Hortorum Cultus*, 17(4), 93-107.
- Arumugam, E., Venkatasamy, B., Marimuthu, M., Muthurajan, R., Rajasekaran, R., Gothandaraman, R., & Eswaran, K. (2026). Molecular profiling and screening of indigenous *Bacillus thuringiensis* (Bt) isolates against *Henosepilachna vigintioctopunctata* (Coleoptera: coccinellidae). *International Journal of Tropical Insect Science*, 1-13.
- Atinga, D. A. V. I. D. (2019). *Agricultural technology adoption and market participation among smallholder rice farmers in Northern Ghana* (Doctoral dissertation).
- Barnett, A. G., Van Der Pols, J. C., & Dobson, A. J. (2005). Regression to the mean: what it is and how to deal with it. *International journal of epidemiology*, 34(1), 215-220.
- Bayo, S. J. (2025). *Enhancing Banana (Musa Acuminata) Breeding Efficiency: Genotypic Pollen Performance and The Influence of Irrigation And Potassium on Seed Set and Viability* (Doctoral dissertation, Nelson Mandela Institution of Science and Technology).
- Becker, M. F., Hellmann, M., & Knief, C. (2022). Spatio-temporal variation in the root-associated microbiota of orchard-grown apple trees. *Environmental microbiome*, 17(1), 31.
- Bhattacharyya, C., Banerjee, S., Acharya, U., Mitra, A., Mallick, I., Halder, A., ... & Ghosh, A. (2020). Evaluation of plant growth promotion properties and induction of antioxidative defense mechanism by tea rhizobacteria of Darjeeling, India. *Scientific reports*, 10(1), 15536.
- BISWAS, A. (2025). *Phosphate sorption and desorption characteristics in submerged lateritic soil influenced by different phosphatic fertilizers* (doctoral dissertation, dr. Balasaheb sawant konkan krishi vidyapeeth).
- Bubici, G., Kaushal, M., Prigigallo, M. I., Gómez-Lama Cabanás, C., & Mercado-Blanco, J. (2019). Biological control agents against *Fusarium* wilt of banana. *Frontiers in microbiology*, 10, 616.
- Chaudhari, S. K., & Singh, A. (2019). NRM interventions for enhanced mango productivity and quality. *World*, 3, 9-29.
- Chavan, A., Wahane, M., Khobragade, N., Damodhar, V., Dodake, S., Prasad, J., & Ramteke, I. (2026). Spatial variability and multivariate assessment of soil properties and nutrient availability in mango-supporting soils of the Western Ghats, India. *Environmental Monitoring and Assessment*, 198(2), 200.
- Dita, M., Barquero, M., Heck, D., Mizubuti, E. S., & Staver, C. P. (2018). *Fusarium* wilt of banana: current knowledge on epidemiology and research needs toward sustainable disease management. *Frontiers in plant science*, 9, 1468.
- Dubey, A., Malla, M. A., Khan, F., Chowdhary, K., Yadav, S., Kumar, A., ... & Khan, M. L. (2019). Soil microbiome: a key player for conservation of soil health under changing climate. *Biodiversity and Conservation*, 28(8), 2405-2429.
- Dzanku, F. (2018). Perspectives on Agriculture, Diversification, and Gender in Rural Africa: Theoretical and Methodological Issues. *Oxford Scholarship Online*.
- Faostat, F. A. O. (2022). *Crops and livestock products*.
- Fuchs, A. (2026). Standortbouquets. *Bloom–Eine transdisziplinäre Annäherung an Blumen/A Transdisciplinary Exploration of Flowers*, 186.
- Gaurishankar, b. D. (2021). *Economic analysis of exotic vegetable production in lahaul & spiti district of himachal pradesh* (doctoral dissertation, chaudhary sarwan kumar himachal pradesh krishi vishvavidyalaya).
- Gillingham, K., & Palmer, K. (2014). Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. *Review of Environmental Economics and Policy*.
- Gupta, A. (2022). Green Economy and Sustainable Development Concept of New India. *ANKIT PUBLICATION Jagriti Nagar, Manduadih Varanasi-221103 (UP)*.
- Hazarika, T. K. (2023). Citrus. In *Fruit and nut crops* (pp. 1-44). Singapore: Springer Nature Singapore.
- Ignjatov, M. V. (2019). Integration of biological and conventional treatments in control of pepper bacterial spot. *Crop Protection*.
- Jagannath, e. C. V. (2017). *Development and evaluation of solar energy based cashew apple ethanol production system* (doctoral dissertation, dr. Balasaheb sawant konkan krishi vidyapeeth).
- Kazadi, A. T., Lwalaba, J. L. W., Ansey, B. K., Muzulukwau, J. M., Katabe, G. M., Karul, M. I., ... & Mundende, R. P. M. (2022). Effect of phosphorus and arbuscular mycorrhizal fungi (AMF) inoculation on growth and productivity of maize (*Zea mays* L.) In a tropical ferralsol. *Gesunde Pflanzen*, 74, 159-165.
- Kumar, A., Borisova, G., Maleva, M., Tripti, Shiryayev, G., Tugbaeva, A., ... & Kiseleva, I. (2022). Biofertilizer based on biochar and metal-tolerant plant growth promoting rhizobacteria alleviates copper impact on morphophysiological traits in *Brassica napus* L. *Microorganisms*, 10(11), 2164.
- Kumar, B., Mistry, N. C., Singh, B., & Gandhi, C. P. (2011). Indian horticulture database. *National Horticulture Board. Ministry of Agriculture, Government of India*.

- Kumari, D., Gupta, N., Sharma, N., & Kumar, V. (2025). From Root to Fruit: Mycorrhizal Impact on Fruit Crops. In *Sustainable Mycorrhizal Cultivation: Innovations for Hillside Farming Systems* (pp. 147-168). Singapore: Springer Nature Singapore.
- Kushwaha, S. (2020). Effect of bacterial consortium on performance of chickpea in agroclimatic condition of Chhattishgarh plain. *M. Sc. (Ag.)*
- Lahlali, R., Ezrari, S., Radouane, N., Kenfaoui, J., Esmaeel, Q., El Hamss, H., ... & Barka, E. A. (2022). Biological control of plant pathogens: A global perspective. *Microorganisms*, 10(3), 596.
- Lamichhane, J. R., Osdaghi, E., Behlau, F., Köhl, J., Jones, J. B., & Aubertot, J. N. (2018). Thirteen decades of antimicrobial copper compounds applied in agriculture. A review. *Agronomy for sustainable development*, 38(3), 28.
- Lee, Y., Yeoung, H., Mezzetti, B., & Yeoung, Y. (2026). Strawberry propagation: Progress on propagation methods, environmental regulation, and disease management strategies over the past 20 years. *Horticulturae*, 12(3), 351.
- Lokesh Bora, L. B., Arunima Tripathi, A. T., Jyoti Bajeli, J. B., Chaubey, A. K., & Subhash Chander, S. C. (2016). A review on microbial association: its potential and future prospects in fruit crops.
- Ma, Y., Liu, H., Yu, Y., Guo, L., Zhao, W., & Yetemen, O. (2022). Revisiting soil water potential: Towards a better understanding of soil and plant interactions. *Water*, 14(22), 3721.
- Maan, S. A., & Abdelhamid, S. A. (2026). Molecular identification and optimization of indole acetic acid production by *Fusarium oxysporum* AUMC 16,438 for biofertilizer application. *Scientific Reports*, 16(1), 3474.
- Maden, R. R. (2024). *An Agroecological Approach to Improving Soil Health Practices on Vermont Vegetable Farms*. The University of Vermont and State Agricultural College.
- Mechler, M. (2024). *Alternative Treatments for Apple Replant Disease* (Doctoral dissertation, University of Guelph).
- Meena, K. K., Sorty, A. M., Bitla, U. M., Choudhary, K., Gupta, P., Pareek, A., ... & Minhas, P. S. (2017). Abiotic stress responses and microbe-mediated mitigation in plants: the omics strategies. *Frontiers in plant science*, 8, 172.
- Minich, D. M., Ross, K., Frame, J., Fahoum, M., Warner, W., & Meissner, H. O. (2024). Not all maca is created equal: A review of colors, nutrition, phytochemicals, and clinical uses. *Nutrients*, 16(4), 530.
- Morelli, R., Zanzotti, R., Bertoldi, D., & Zanoni, S. (2023). Nitrogen in apple orchards under integrated and organic farming. In *IV Convegno AISSA# under 40, Fisciano (SA)*, 12-13 luglio 2023 (p. 228). IT.
- Patel, D., & Goswami, D. (2020). Phosphorus solubilization and mobilization: mechanisms, current developments, and future challenge. In *Advances in plant microbiome and sustainable agriculture: functional annotation and future challenges* (pp. 1-20). Singapore: Springer Singapore.
- Patel, D., Jha, C. K., Tank, N., & Saraf, M. (2012). Growth enhancement of chickpea in saline soils using plant growth-promoting rhizobacteria. *Journal of Plant Growth Regulation*, 31(1), 53-62.
- Pereira, A. C. (2026). From carbonaceous residues to engineered fertilizers: A performance-first critical review of biochar and hydrochar for nutrient recovery, controlled release, agronomic function, and life-cycle climate performance. *Journal International Review of Research Studies*, 1(08-August), 1-58.
- Phadke, g. S. (2016). *Survey of arbuscular mycorrhizal fungi and their application as bio-fertilizer in mangifera indica* (doctoral dissertation, University of Mumbai).
- Porter, S. D. (2019). *Production-phase greenhouse gases embedded within food loss and waste: magnitude, drivers, and mitigation potential* (Doctoral dissertation, University of Edinburgh).
- Pscheidt, J. W., & Ocamb, C. M. (2022). Copper-based bactericides and fungicides. *Pacific Northwest pest management handbooks. Oregon State University, Corvallis*.
- Raghuvanshi, R. S., Milan, A., Sharma, B., Raghuwaanshi, S., Bag, D., Nigam, R., ... & Dhiman, S. (2025). A review on sustainable plant disease management through integrated approaches. *Journal of Experimental Agriculture International*, 47(12), 719-739.
- Saha, K., Kumar, K. A., Karthika, K. S., Hegde, R., & Prasad, J. (2023). Distribution of nutrients and their indexing in major mango-supporting soils of different agro-climatic zones of Karnataka and its impact on yield. *Journal of Applied Horticulture*, 25(2), 144-148.
- Salas, B. B843: The Ecology, Economics, and Management of Potato Cropping Systems: A Report of the First Four Years of the Maine Potato Ecosystem Project.
- Sarker, A., Mitra, D., Das Mohapatra, P. K., Ansary, M. W. R., & Islam, T. (2022). Plant growth-promoting rhizobacteria as biostimulants in sustainable crop production. In *Biostimulants for crop production and sustainable agriculture* (pp. 455-483). GB: CABI.
- Šević, M., Gašić, K., Ignjatov, M., Mijatović, M., Prokić, A., & Obradović, A. (2019). Integration of biological and conventional treatments in control of pepper bacterial spot. *Crop Protection*, 119, 46-51.
- Shang, X., Nie, Y., Wang, P., Cao, H., Hijri, M., Lee, S. J., ... & Wang, L. (2026). Arbuscular mycorrhizal fungal symbiosis enhances crop

- photosynthetic traits under drought stress—a meta-analysis. *Agriculture*, 16(11), 1180.
- Sharma, L., Jaiswal, V. P., Shukla, S. K., Rawat, L., & Gaur, A. (2026). Integration of novel endophytic diazotrophs with reduced nitrogen fertilization improves nitrogen uptake and productivity in sugarcane in subtropical India. *Plant and Soil*, 1-17.
- Sharma, N., Vittal, H., Dubey, A. K., Sharma, R. M., Singh, S. K., Sharma, N., ... & Singh, N. K. (2025). Physiological and molecular insights into alternate bearing in mango using next-generation sequencing approaches. *Journal of Experimental Botany*, 76(6), 1585-1606.
- Shereni, C. (2019). *Use of biostimulants as an alternate approach to achieve plant performance and fruit quality* (Doctoral dissertation, Stellenbosch: Stellenbosch University).
- Singh, H. P., & Singh, B. (2020). Banana research and development in India-a review. *International Journal of innovative horticulture*, 9(2), 71-6.
- Sivasakthivelan, P., Saranraj, P., Sayyed, R. Z., Arivukkarasu, K., Kokila, M., Manigandan, M., & Seifi, S. (2023). Inoculant production and formulation of *Azospirillum* species. In *Plant growth promoting microorganisms of arid region* (pp. 423-455). Singapore: Springer Nature Singapore.
- Smit, R., Ayala, A., Kadijk, G., & Buekenhoudt, P. (2025). Excess pollution from vehicles—A review and outlook on emission controls, testing, malfunctions, tampering, and cheating. *Sustainability*, 17(12), 5362.
- Stander, O. P. J. (2018). *Critical factors concomitant to the physiological development of alternate bearing in citrus (Citrus spp.)* (Doctoral dissertation, Stellenbosch: Stellenbosch University).
- Tang, C., Zhang, Z., Yu, L., & Li, Y. (2023). Research progress of arbuscular mycorrhizal fungi promoting citrus growth. *Horticulturae*, 9(11), 1162.
- Trivedi, P., Leach, J. E., Tringe, S. G., Sa, T., & Singh, B. K. (2020). Plant-microbiome interactions: from community assembly to plant health. *Nature reviews microbiology*, 18(11), 607-621.
- Tsai, W. H., & Lai, S. Y. (2018). Green production planning and control model with ABC under industry 4.0 for the paper industry. *Sustainability*, 10(8), 2932.
- Van Zwieten, L., Kimber, S., Downie, A., Morris, S., Petty, S., Rust, J., & Chan, K. Y. (2010). A glasshouse study on the interaction of low mineral ash biochar with nitrogen in a sandy soil. *Soil Research*, 48(7), 569-576.
- Vital, D. F. (2023). *Study of the Effectiveness of Two Natural Amendments in Mitigating the Availability of Cu in Agricultural Viticulture Soil* (Master's thesis, Universidade do Porto (Portugal)).
- Wan, L. J., Tian, Y., He, M., Zheng, Y. Q., Lyu, Q., Xie, R. J., ... & Yi, S. L. (2021). Effects of chemical fertilizer combined with organic fertilizer application on soil properties, citrus growth physiology, and yield. *Agriculture*, 11(12), 1207.
- Yadav, s. S. (2023). *Study on knowledge and adoption extent of organic fertilizers among the farmers in sursa block of hardoi district (uttar pradesh)* (doctoral dissertation, chandra shekhar azad university of agriculture & technology).