E-ISSN:2583-553X

Research Article

Biofertilizers

Applied Science and Biotechnology Journal for Advanced Research

2026 Volume 5 Number 3 May

Publisher

Vandana Publications
www.vandanapublications.com

Biofertilizers and Biopesticides in Sustainable Agriculture: Mechanisms, Applications, Constraints, and Emerging Directions—A Review

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DOI:10.31033/ABJAR/5.3.2026.125

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Modern agriculture needs high productivity, but it also needs healthy soil, clean water and safer pest management. Heavy and poorly managed use of synthetic fertilizers and chemical pesticides can disturb nutrient balance, increase pollution, leave residues and select resistant pest populations. Biofertilizers and biopesticides offer a different route. Biofertilizers use beneficial microorganisms to improve nutrient availability, root growth and plant tolerance to stress. Biopesticides use microorganisms, plant products, natural compounds or other biological agents to suppress insects, pathogens, nematodes and weeds. This review brings these two groups together and examines how they can support sustainable crop production. It discusses major biofertilizers such as rhizobia, *Azotobacter, Azospirillum*, phosphate- and potassium-solubilizing microorganisms, arbuscular mycorrhizal fungi, cyanobacteria and microbial consortia. It also reviews important biopesticides, including *Bacillus thuringiensis, Trichoderma, Pseudomonas, Bacillus*, entomopathogenic fungi, baculoviruses, entomopathogenic nematodes, neem products and pheromones. The strongest value of these inputs appears when farmers integrate them with balanced fertilization, organic matter management, resistant cultivars, crop rotation and integrated pest management rather than use them as isolated replacements. Field performance, however, remains variable. Shelf life, formulation quality, environmental sensitivity, product standards and farmer handling all matter. Research reported through December 2025 shows a clear shift toward synthetic microbial communities, microbiome-guided strain selection, multi-omics, improved fermentation, encapsulation, nano-enabled delivery and precision application. These advances are promising, but laboratory success must be matched by reproducible field evidence and strong biosafety assessment. Better products will come from locally adapted strains, transparent quality control and realistic recommendations for farmers.

Keywords: biofertilizers, biopesticides, sustainable agriculture, plant growth-promoting rhizobacteria, biological control, soil health, integrated pest management, microbial inoculants

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Sandeep Kumar, Associate Professor, Department of Botany, Meerut College, Meerut, Uttar Pradesh, India. Email: sandeep.kumar@mcm.ac.in	Shiwach E, Kumar S, Biofertilizers and Biopesticides in Sustainable Agriculture: Mechanisms, Applications, Constraints, and Emerging Directions—A Review. Appl Sci Biotechnol J Adv Res. 2026;5(3):72-83. Available From https://abjar.vandanapublications.com/index.php/ojs/article/view/125	

Manuscript Received	Review Round 1	Review Round 2	Review Round 3	Accepted
2026-04-20	2026-05-07			2026-05-25
Conflict of Interest	**Funding**	**Ethical Approval**	**Plagiarism X-checker**	**Note**
None	Nil	Yes	5.71	

1. Introduction

Agriculture has increased food production greatly during the last century. Much of that gain came from improved crop varieties, irrigation, fertilizers and pesticides. These tools remain important. The problem begins when inputs are used in excess, at the wrong time, or without regard to soil and ecological conditions. High nitrogen inputs can increase nitrate loss, soil acidification and nitrous oxide emissions. Repeated phosphorus inputs may accumulate in soil or move into water. In the same way, repeated pesticide use can leave residues, harm useful organisms and favour resistant pest populations (Galloway et al., 2008; Carpenter, 2008; Chandler et al., 2011; Ayilara et al., 2023).

Sustainable agriculture does not mean farming without all external inputs. It means using them more wisely and reducing avoidable damage. Biological inputs can help in this transition. Biofertilizers improve nutrient supply through living microorganisms, while biopesticides control pests through biological or naturally derived agents. Their roles overlap in some cases. For example, strains of *Bacillus*, *Pseudomonas* and *Trichoderma* may promote plant growth and also suppress disease (Harman et al., 2004; Backer et al., 2018).

The idea is simple, but the biology is not. A microbial inoculant must survive production, storage, transport and application. Then it must reach the plant, compete with native microorganisms and remain active under changing temperature, moisture and soil conditions. A biopesticide faces similar problems. It may work very well in the laboratory and still fail in a dry field under strong sunlight. This gap between biological potential and field reliability is one of the central themes in current research (Bashan et al., 2014; Fadiji et al., 2024; Díaz-Rodríguez et al., 2025).

Recent work has moved beyond the search for a single 'best' strain. Researchers now study whole plant microbiomes, synthetic microbial communities, metabolite profiles, genome information and smarter delivery systems. At the same time, biopesticide research is paying more attention to formulation, scale-up, integrated pest management and cost-effective field use (Singh et al., 2025; Shahzad et al., 2025; Marrone, 2025; Mawcha et al., 2025).

This review examines these developments while keeping a practical question in view: how can biological inputs become more reliable tools for farmers?

2. Scope and Approach of This Review

This article is a narrative review of biofertilizers and biopesticides in sustainable agriculture. It synthesizes established literature together with relevant peer-reviewed studies and reviews available. The emphasis is on mechanisms, major biological agents, crop use, formulation, field constraints, integration with nutrient and pest management, and recent technological directions.

The review does not treat every commercial product or every microbial species. Instead, it focuses on representative groups that have strong agricultural relevance or a clear research base. Older landmark papers are retained where they explain well-established mechanisms, while recent studies are used to show how the field is changing. This approach is useful because biofertilizer and biopesticide research now spans soil microbiology, plant physiology, ecology, formulation science, genomics and pest management.

3. Biofertilizers: Biological Basis and Major Groups

Biofertilizers are preparations that contain beneficial living or dormant microorganisms. These organisms colonize the rhizosphere, root surface or internal plant tissues and improve plant growth by making nutrients more available or by helping roots acquire them more efficiently (Vessey, 2003; Malusá & Vassilev, 2014; Santos et al., 2024). They are not simply dilute chemical fertilizers. In most cases, they do not add large amounts of nitrogen, phosphorus or potassium directly. They change biological processes around the plant.

This distinction matters. A bag of compost adds organic matter and nutrients. A biofertilizer adds selected biological activity. Some products combine both, but the expected effect still depends on the survival and function of the inoculated organism (Bashan et al., 2014). Recent reviews also show that the word 'biofertilizer' is used differently across countries and regulatory systems.

That inconsistency can confuse product claims and quality standards (Santos et al., 2024; Díaz-Rodríguez et al., 2025).

3.1 Nitrogen-fixing Microorganisms

Symbiotic nitrogen fixation is the best-known biofertilizer process. *Rhizobium*, *Bradyrhizobium*, *Mesorhizobium* and related bacteria form nodules on legume roots. Inside these nodules, nitrogenase converts atmospheric nitrogen into forms the plant can use. Good inoculation can supply a large part of a legume's nitrogen need, but the outcome depends on the strain, host genotype and field environment (Vessey, 2003). Soil acidity, salinity, temperature, moisture, mineral nitrogen and competition from native rhizobia can all change nodulation.

Free-living and associative nitrogen fixers broaden the concept. *Azotobacter* lives freely in soil, while *Azospirillum* commonly associates with roots of cereals and grasses. Their benefit is not due to nitrogen fixation alone. They can also produce growth regulators, siderophores and other metabolites that change root architecture and nutrient uptake (Bhattacharyya & Jha, 2012; Backer et al., 2018). Endophytic genera such as *Gluconacetobacter*, *Herbaspirillum* and *Azoarcus* are also important because internal colonization may protect them from some of the competition found in bulk soil.

3.2 Phosphorus, Potassium and Micronutrient Mobilizers

Soils often contain far more total phosphorus than plants can immediately absorb. Much of it is fixed in poorly soluble mineral forms or bound in organic matter. Phosphate-solubilizing bacteria and fungi release organic acids, protons and enzymes such as phosphatases and phytases. These reactions can increase plant-available phosphorus (Sharma et al., 2013; Alori et al., 2017; Cheng et al., 2023). *Bacillus* and *Pseudomonas* are common bacterial examples, while *Aspergillus*, *Penicillium* and *Trichoderma* include important fungal solubilizers.

Potassium-solubilizing bacteria act on mineral sources of potassium, especially silicate minerals. Genera such as *Bacillus*, *Paenibacillus*, *Pseudomonas* and *Frateuria* have been studied for this role. Other microbes can mobilize zinc, sulphur and iron.

Siderophore-producing organisms are especially interesting because iron capture can support plant nutrition while limiting iron availability to some pathogens (Bhattacharyya & Jha, 2012; Backer et al., 2018).

3.3 Arbuscular Mycorrhizal Fungi, Cyanobacteria and *Azolla*

Arbuscular mycorrhizal fungi form close associations with the roots of many crops. Their hyphae grow beyond the nutrient-depleted zone around roots and explore a larger soil volume. This is especially useful for phosphorus and zinc, which move slowly in soil. Mycorrhizal fungi can also improve soil aggregation, water relations and plant tolerance to drought or salinity (Begum et al., 2019; Delaeter et al., 2024). Yet high phosphorus fertilizer can reduce root colonization and weaken the benefit of inoculation.

Nitrogen-fixing cyanobacteria are particularly useful in flooded rice systems. *Anabaena*, *Nostoc*, *Aulosira* and related forms add biologically fixed nitrogen and biomass. *Azolla* adds another layer. This floating fern carries a nitrogen-fixing cyanobacterial partner in its leaf cavities and can be grown as green manure in rice fields. These systems are old examples of biological nutrient management, but they remain relevant where water and crop conditions favour them.

3.4 From Single Strains to Microbial Consortia

A single organism rarely performs every useful function. This has driven interest in microbial consortia. A consortium may combine nitrogen fixation, phosphorus solubilization, potassium mobilization, root stimulation and disease suppression. In principle, several mechanisms can operate together and make performance more stable. In practice, compatibility is not guaranteed. One strain may suppress another, grow faster during storage, or respond differently to soil conditions (Niu et al., 2017; Toju et al., 2018).

The newer term synthetic microbial community, or SynCom, describes a deliberately assembled set of microorganisms with defined functions. Researchers now use ecological rules, genome information and functional screening to design these communities rather than simply mixing available strains. Reviews published in 2025 emphasize their potential for nutrient acquisition, stress tolerance and disease control, but also note that reproducibility and field persistence are still major challenges (Singh et al., 2025; Tariq et al., 2025).

Table 1: Major biofertilizer groups and their main agricultural roles

Group	Representative organisms	Main role	Typical use
Symbiotic nitrogen fixers	Rhizobium, Bradyrhizobium, Mesorhizobium	Nitrogen fixation in root nodules	Legumes, pulses, fodder crops
Free-living/ associative nitrogen fixers	Azotobacter, Azospirillum, Gluconacetobacter	Nitrogen contribution, root stimulation, growth promotion	Cereals, millets, sugarcane, vegetables
Phosphate-solubilizing microbes	Bacillus, Pseudomonas, Aspergillus, Penicillium	Release of poorly available soil phosphorus	Cereals, pulses, oilseeds, vegetables
Potassium and micronutrient mobilizers	Frateuria, Bacillus, Paenibacillus, Thiobacillus	Mobilization of K, Zn, Fe or S	Nutrient-deficient soils and diverse crops
Arbuscular mycorrhizal fungi	Rhizophagus, Funneliformis, Claroideoglomus	Improved P/Zn uptake, water relations and soil aggregation	Field, horticultural and forestry crops
Cyanobacteria and Azolla systems	Anabaena, Nostoc, Aulosira; Azolla–Anabaena association	Biological N fixation and biomass addition	Lowland rice systems
Microbial consortia/ SynComs	Compatible bacterial and/or fungal communities	Multiple complementary functions in one inoculant	Emerging use across crop systems

4. How Biofertilizers Promote Plant Growth

Biofertilizers act through several direct and indirect mechanisms. Nitrogen fixation is the most obvious. Nitrogenase reduces atmospheric nitrogen to ammonia, which then enters plant and microbial metabolism. In legumes, this process can reduce the need for external nitrogen and may also leave residual nitrogen for the next crop (Vessey, 2003).

Nutrient solubilization works differently. Microorganisms release acids, chelators and enzymes that free nutrients from minerals or organic matter. The local chemistry around a microbial colony can therefore be very different from the bulk soil. A small change in pH near the root may release phosphorus or potassium that was previously unavailable (Sharma et al., 2013; Alori et al., 2017).

Many plant growth-promoting rhizobacteria also produce auxins, gibberellins or cytokinins. Indole-3-acetic acid can increase lateral roots and root hairs.

More roots mean more contact with soil, more sites for microbial colonization and often better water and nutrient uptake (Bhattacharyya & Jha, 2012; Backer et al., 2018). This effect can be more important than the amount of nitrogen fixed by some associative bacteria.

Stress biology adds another mechanism. Some bacteria produce 1-aminocyclopropane-1-carboxylate deaminase, usually called ACC deaminase. The enzyme lowers the amount of ACC available for stress ethylene formation. Under drought, salinity, waterlogging or other stress, this can help roots continue growing (Glick, 2004; Backer et al., 2018).

Beneficial microorganisms also influence soil structure and microbial competition. Fungal hyphae and microbial polysaccharides help form stable soil aggregates. Siderophores bind iron. Antibiotics and volatile compounds can suppress competitors. These processes show why a biofertilizer cannot be judged only by the amount of one nutrient released in a laboratory test. Its value may come from several small biological effects acting together.

5. Biopesticides: Types and Modes of Action

Biopesticides are pest-control products based on microorganisms, plant-derived substances, naturally occurring biochemicals or other biological agents. They can target insects, mites, fungal and bacterial pathogens, nematodes and, in some cases, weeds (Chandler et al., 2011; Ayilara et al., 2023; Mawcha et al., 2025). Many are more target-specific and less persistent than broad-spectrum synthetic pesticides. That can be an advantage. It can also make timing and pest identification more important.

The word 'natural' should not be used as a shortcut for 'safe.' Every active agent needs proper evaluation. Host range, toxicity, environmental persistence and effects on non-target organisms still matter (Glare et al., 2012; Ayilara et al., 2023; Fenibo & Matambo, 2025).

5.1 Bacterial and Fungal Biopesticides

Bacillus thuringiensis, or Bt, is the classic microbial insecticide. During sporulation it produces insecticidal crystal proteins. Susceptible larvae ingest the proteins, which become active in the gut, bind to receptors and damage the midgut epithelium (Bravo et al., 2011). Bt products can be highly selective. This reduces harm to many non-target organisms, but it also means that the farmer must identify the pest correctly and spray when larvae are at a susceptible stage.

Other *Bacillus* species and *Pseudomonas fluorescens* are used mainly against plant diseases. They compete for nutrients and colonization sites, release antibiotics or siderophores, secrete enzymes and can activate plant defence responses. The same strain may also stimulate root growth. This is one reason the border between biofertilizer and biopesticide is not always sharp (Backer et al., 2018).

Trichoderma species are among the most studied fungal biocontrol agents. They compete strongly in the rhizosphere, parasitize other fungi, produce inhibitory metabolites and release cell-wall-degrading enzymes such as chitinases and glucanases. They can also induce plant resistance and improve root growth (Harman et al., 2004; Poveda, 2021). Their broad set of functions makes them useful, but strain identity and formulation quality remain critical.

5.2 Entomopathogenic Fungi, Viruses and Nematodes

Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* infect through the insect cuticle. Spores attach, germinate and penetrate the body wall. The fungus then grows inside the host and disrupts normal physiology. Because ingestion is not required, these fungi can attack insects that are difficult to control with stomach poisons. Their weakness is environmental sensitivity. Humidity, temperature and ultraviolet radiation can strongly affect infection and persistence (Jackson et al., 2010; Lacey et al., 2015).

Baculoviruses, especially nucleopolyhedroviruses and granuloviruses, are very specific insect pathogens. They have been used against pests such as *Helicoverpa armigera* and *Spodoptera litura*. Their narrow host range helps protect beneficial insects, but mortality is often slower than with contact insecticides. Strong sunlight can also reduce activity. Good timing, therefore, matters (Lacey et al., 2015).

Entomopathogenic nematodes in the genera *Steinernema* and *Heterorhabditis* carry symbiotic bacteria that kill susceptible insects after the nematodes enter the host. They work particularly well against soil-inhabiting stages when soil moisture and temperature are suitable (Lacey et al., 2015).

5.3 Botanical Pesticides and Semiochemicals

Plants produce many compounds that affect insects and pathogens. Neem is the best-known example. Azadirachtin from *Azadirachta indica* can reduce feeding, disturb moulting and development, and lower reproduction. Pyrethrins, essential oils, garlic extracts, chilli extracts and several other plant products have also been used or studied as biopesticides (Isman, 2020; Ayilara et al., 2023).

Botanical pesticides often break down quickly in the environment. Lower persistence can reduce long-term residues, but short persistence may also reduce field efficacy and increase the need for repeated application. Composition can vary with plant genotype, growth conditions, extraction method and storage. Formulation is therefore a central issue, not a minor technical detail (Isman, 2020).

Semiochemicals use insect behaviour rather than direct toxicity. Pheromones can support monitoring, mass trapping and mating disruption. They are highly species-specific, which is useful for decision-making in integrated pest management. A pheromone trap may not kill enough insects by itself, but it can tell a farmer when the pest is active and when another control measure is likely to work best (Witzgall et al., 2010).

Table 2: Important biopesticide groups, examples and main modes of action

Category	Examples	Targets	Main action
Bacterial insecticides	Bacillus thuringiensis	Caterpillars, beetles, mosquito larvae	Insecticidal proteins damage the midgut
Bacterial antagonists	Bacillus subtilis, Pseudomonas fluorescens	Plant-pathogenic fungi and bacteria	Competition, antibiosis, siderophores, induced resistance
Fungal antagonists	Trichoderma harzianum, T. viride	Soil-borne fungal pathogens	Mycoparasitism, enzymes, metabolites, competition

Entomo-pathogenic fungi	Beauveria bassiana, Metarhizium anisopliae	Insect pests	Cuticle penetration followed by internal infection
Viral bio-pesticides	Baculoviruses (NPVs and GVs)	Mainly lepidopteran larvae	Viral replication and destruction of host tissues
Entomo-pathogenic nematodes	Steinernema, Heterorhabditis	Soil-inhabiting insects	Nematode entry and release of symbiotic bacteria
Botanical pesticides	Neem, pyrethrum, essential oils	Insects, mites and some pathogens	Antifeedant, repellent, toxic or growth-disrupting effects
Semio-chemicals	Pheromones and attractants	Specific insect species	Monitoring, trapping and mating disruption

6. Integration with Nutrient and Pest Management

Biological inputs work best when they are part of a management system. A biofertilizer cannot correct every soil problem, and a biopesticide cannot rescue every severe pest outbreak. This is not a weakness of the concept. It is a reminder that crop production is a system.

Integrated nutrient management combines soil testing, crop residues, manures, legumes, balanced mineral fertilizers and biological inputs. Rhizobial inoculation, for example, performs better when other limiting nutrients such as phosphorus or sulphur are corrected. Phosphate-solubilizing microorganisms may be used with rock phosphate or with reduced doses of soluble phosphorus fertilizers. Mycorrhizal inoculation may fit well with organic amendments and reduced tillage, but very high phosphorus inputs can suppress the symbiosis (Vessey, 2003; Alori et al., 2017; Begum et al., 2019; Shahzad et al., 2025).

The same principle applies to pest management. Biopesticides fit naturally into integrated pest management because IPM uses monitoring, crop rotation, sanitation, resistant varieties, cultural methods, biological control and selective pesticides together. Many biological agents work best before pest populations become very high. Early application can prevent disease establishment or suppress young insect stages. Waiting for heavy damage and then expecting an immediate knock-down effect often leads to disappointment (Chandler et al., 2011; Glare et al., 2012; Marrone, 2025).

Integration also helps slow resistance. A biological product with a different mode of action can be rotated with other control tools. Still, biological agents are not resistance-proof. Repeated exposure to the same active ingredient can select for less susceptible populations. Good stewardship remains necessary.

7. Formulation, Delivery and Product Stability

A useful microorganism is not yet a useful product. The formulation must keep it alive, stable and easy to apply. Carrier-based biofertilizers use materials such as peat, lignite, charcoal, talc, vermiculite or compost. The carrier protects cells and helps deliver them to seed or soil. Liquid formulations place cells in protective solutions and can simplify application, but they still require strong contamination control and stable storage conditions (Bashan et al., 2014; Fadiji et al., 2024).

Application method also matters. Seed treatment places the organism close to the emerging root and is usually economical. Root dipping is common for transplanted crops. Soil application may be used when the target is the rhizosphere or a soil-borne pest. Foliar sprays suit many microbial antagonists, Bt products, entomopathogenic fungi and botanical pesticides. Each route exposes the active agent to a different set of stresses.

Encapsulation can protect cells or active compounds inside alginate, starch or other matrices and release them slowly. Nano-enabled formulations extend the same idea to very small carriers. They can improve solubility, adhesion, stability and controlled release, especially for plant-derived compounds that break down quickly. Recent work on azadirachtin showed how a designed nanocarrier can protect and release the neem active ingredient over time (Jokarshourijeh et al., 2025). A 2025 systematic review of botanical nanoformulations also found strong laboratory promise, but emphasized that field testing and scalability still lag behind laboratory research (Luneja & Mkindi, 2025).

Nanoformulation should not be treated as automatically safer because the active ingredient is biological. Nanomaterials can behave differently from conventional carriers in soil, water and organisms. Their environmental fate, non-target effects and persistence need direct study (Ayilara et al., 2023; Luneja & Mkindi, 2025).

8. Benefits for Sustainable Agriculture: Evidence and Caution

Biofertilizers and biopesticides can reduce dependence on synthetic inputs, but the size of that reduction varies. Nitrogen-fixing organisms can replace part of the nitrogen requirement in suitable crops. Nutrient-solubilizing organisms may improve the use of nutrients already present in soil. Biopesticides can reduce the number or dose of conventional pesticide applications when pest pressure and timing are appropriate (Vessey, 2003; Glare et al., 2012).

Soil health is another major benefit. Root-associated microbes support nutrient cycling, root development and soil aggregation. Mycorrhizal fungi connect roots with a larger soil volume. Some PGPR improve plant responses to drought and salinity. These effects can support resilience, especially when biological inputs are combined with organic matter and good soil management (Backer et al., 2018; Begum et al., 2019).

Biopesticides may also conserve beneficial organisms because many are more selective than broad-spectrum pesticides. Lower persistence can reduce long-term residues. These features fit well with ecological pest management, pollinator protection and conservation biological control (Glare et al., 2012; Lacey et al., 2015).

There is, however, a danger in overselling. A biological product is not effective simply because it contains a useful organism. Performance depends on strain quality, viable count, formulation, storage, crop, soil and weather. Claims such as 'replace all fertilizer' or 'control all pests' should be treated with caution unless they are supported by well-designed field trials. Recent reviews continue to identify variable field response as one of the largest barriers to wider use (Fadiji et al., 2024; Díaz-Rodríguez et al., 2025).

9. Why Field Performance Often Varies

The field is a harsh test. A strain selected in a laboratory may face acidic soil, drought, heat, native competitors, pesticide residues and a crop genotype it has never encountered. Root exudates also differ among cultivars and growth stages. These variables help explain why greenhouse success does not always translate into yield gains in farmers' fields (Backer et al., 2018; Díaz-Rodríguez et al., 2025).

Shelf life is another practical limit. Living cells lose viability during storage, especially under heat, desiccation or contamination. Fungal spores and viral products can also lose activity if formulation and storage are poor. Cold chains can help but increase cost. Better carriers, protectants and packaging are therefore essential (Bashan et al., 2014; Jackson et al., 2010; Fadiji et al., 2024).

Biopesticides often act more slowly than contact insecticides. That does not mean they are inactive. Feeding, movement or reproduction may fall before mortality becomes obvious. Farmers who expect rapid knock-down may spray again too soon or abandon the product. Clear recommendations and realistic expectations are part of product performance (Glare et al., 2012; Marrone, 2025).

Quality control is a serious issue. A label may name the right species but the product may contain too few viable cells, the wrong strain, contaminants or a weak formulation. For microbial products, identity, purity, viable count, functional activity and shelf life should be measured with validated methods. Product definitions and regulatory categories also need greater consistency across regions (Malusá & Vassilev, 2014; Santos et al., 2024; Díaz-Rodríguez et al., 2025).

Compatibility can be overlooked. A fungicide applied to seed may kill a fungal biofertilizer. A bactericide may reduce the viability of a bacterial inoculant. Some fertilizers, adjuvants and tank mixes can also alter survival or activity. Biological products should therefore be tested in the actual input combinations used by farmers, not only in isolation (Bashan et al., 2014).

Table 3: Major barriers to field use and practical research or management responses

Barrier	Why it occurs	Priority response
Variable field performance	Soil, climate, crop genotype and native microbiome alter colonization	Select locally adapted strains; use multilocation trials; match product to crop and soil
Short shelf life	Loss of viable cells or active propagules during storage	Improve carriers, protectants, packaging and temperature tolerance
Slow pest suppression	Many biological agents do not give rapid knock-down	Apply early; use monitoring and thresholds; integrate with other IPM tools
Environmental sensitivity	UV, rainfall, heat or low humidity reduce persistence	Protective formulations, evening application, better timing and delivery
Quality inconsistency	Wrong strain, low viable count, contamination or weak claims	Standardize identity, purity, viability, potency and shelf-life testing
Agrochemical incompatibility	Seed treatments or tank mixes may inhibit biological agents	Run compatibility tests and provide clear label guidance
Regulatory fragmentation	Definitions and registration pathways differ among regions	Use clear categories, validated claims and risk-based standards
Farmer knowledge gap	Storage, timing and expectations strongly affect outcome	Extension support, simple instructions and demonstration trials

10. Emerging Directions

10.1 Microbiome-guided Products and SynCom Design

Sequencing has changed how researchers see the root zone. A plant interacts with a community, not with one microbe at a time. This has encouraged microbiome engineering and the design of SynComs. Instead of mixing strains randomly, researchers can select organisms with complementary functions and test how they interact as a community (Toju et al., 2018; Singh et al., 2025; Tariq et al., 2025).

This approach may solve part of the consistency problem. A community can contain functional backup: if one strain performs poorly under a particular condition, another may still provide a useful function. Yet the same complexity creates new problems. Population balance can shift during storage or after application. Community members can compete. The host plant and native microbiome may also reorganize the introduced community. Therefore, SynCom design needs ecological testing, not just a longer ingredient list.

10.2 Genomics, Transcriptomics, Proteomics and Metabolomics

Whole-genome sequencing can reveal genes related to nitrogen fixation, nutrient solubilization, antimicrobial production, stress tolerance and toxin synthesis. It can also reveal biosafety concerns, including virulence factors or transferable antimicrobial-resistance genes. Transcriptomics, proteomics and metabolomics then help answer a second question: are these functions actually expressed under realistic conditions? (Toju et al., 2018; Díaz-Rodríguez et al., 2025; Shahzad et al., 2025).

This is a major improvement over selecting strains only by a few plate assays. A phosphate-solubilizing halo is useful, but it does not prove that the strain will colonize roots or release phosphorus in a field soil. Multi-omics can connect genotype, activity and environmental response more directly.

10.3 Better Fermentation, Encapsulation and Controlled Delivery

Mass production must be economical and repeatable. Solid-state and submerged fermentation are being optimized for biomass, spores and active metabolites. After production, the biological material must remain stable. Protective additives, encapsulation and controlled-release systems are therefore becoming central parts of product development (Jackson et al., 2010; Fadiji et al., 2024; Díaz-Rodríguez et al., 2025).

Botanical biopesticides are moving in the same direction. Nanoemulsions and nanocarriers can protect unstable compounds and improve contact with plant or pest surfaces. Research in 2025 strengthened this trend, including controlled-release azadirachtin systems and broader assessment of botanical nanoformulations (Luneja & Mkindi, 2025; Jokarshourijeh et al., 2025). The next test is field realism: cost, scale, residue behaviour, biosafety and farmer usability.

10.4 Multifunctional Biological Inputs

The old division between 'fertilizer microbe' and 'biocontrol microbe' is becoming less useful for some organisms. *Trichoderma*, *Bacillus* and *Pseudomonas* may improve root growth, nutrient acquisition and disease resistance at the same time.

A multifunctional inoculant could reduce the number of separate products a farmer needs (Harman et al., 2004; Backer et al., 2018).

But multifunctionality should be demonstrated, not assumed. A strain that produces an antifungal metabolite in broth may not express it in the rhizosphere. Product labels should therefore distinguish proven functions from possible traits.

10.5 Precision use of Biological Inputs

Precision agriculture can help answer two basic questions: where should a biological product be used, and when? Soil maps, remote sensing, disease forecasting, weather data and decision-support systems can identify fields or time windows where a biological treatment is more likely to succeed. This is especially relevant for biopesticides that are sensitive to humidity, temperature or pest stage (Marrone, 2025; Fenibo & Matambo, 2025).

Precision delivery does not have to mean expensive automation. Even simple use of weather forecasts, pest monitoring and soil testing can improve biological performance. The principle is the same: apply the right organism or product to the right place at the right time.

11. Research Gaps and Future Priorities

The first priority is field validation. Too many promising studies stop after laboratory or greenhouse testing. Biological inputs should be tested across locations, seasons, soil types and crop genotypes. Trials should report not only yield but also colonization, nutrient status, pest pressure, weather and management context. Without this information, a positive or negative result is difficult to interpret (Fadiji et al., 2024; Díaz-Rodríguez et al., 2025).

Second, researchers need better standards for product identity and potency. The species name alone is often not enough because strains within a species can behave very differently. Strain-level identification, viable count, purity, functional assays and shelf-life data should become routine. For consortia, population balance also needs monitoring (Santos et al., 2024; Singh et al., 2025).

Third, local adaptation deserves more attention. A strain isolated from one climate may not perform well in another. Native or locally adapted microorganisms may colonize better because they already tolerate local soil, temperature and moisture conditions. This does not mean local isolates are automatically superior, but they are good candidates for region-specific screening (Toju et al., 2018).Fourth, biosafety assessment must keep pace with innovation. Genome data can help screen microbial inoculants for virulence or resistance genes. Nano-enabled biopesticides need environmental fate and non-target studies. SynComs require attention to community stability and unintended interactions. New technology should improve safety as well as efficacy.

Finally, adoption research is essential. Farmers need products that survive normal storage, fit existing equipment, have clear instructions and deliver economic value. Small gains that occur reliably may be more useful than large gains that appear only under ideal conditions. Extension trials, transparent labels and realistic cost-benefit analysis should therefore be part of biological product development, not an afterthought (Fenibo & Matambo, 2025; Marrone, 2025).

12. Conclusion

Biofertilizers and biopesticides are important tools for sustainable agriculture, but their value is biological, not magical. Biofertilizers can improve nutrient acquisition, root growth and stress tolerance through nitrogen fixation, nutrient mobilization, phytohormones, siderophores and other plant-microbe interactions. Biopesticides can suppress pests through infection, parasitism, competition, antibiosis, behavioural disruption and induced plant defence.

Their strongest role is in integration. Biofertilizers work best with balanced nutrient management, organic matter and suitable crop practices. Biopesticides work best with monitoring, resistant cultivars, cultural control and IPM. When these products are treated as stand-alone replacements for all fertilizers or pesticides, expectations become unrealistic.

Research shows where the field is heading: rational SynCom design, microbiome-based selection, multi-omics, better fermentation, stronger formulations, encapsulation, nano-enabled delivery and precision application. These tools can improve reliability, but they do not remove the need for field testing.

The next generation of biological inputs should be locally adapted, well characterized, safe, easy to use and supported by reproducible evidence. That is the path from promising biology to dependable agriculture.

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