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Harnessing Biofertilizers and Biopesticides for Sustainable Agriculture

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Abstract

Agricultural systems are increasingly affected by soil degradation, declining fertility, crop pests, diseases and climate-related stresses. Conventional farming has relied extensively on synthetic fertilizers and pesticides, but excessive use can contribute to environmental contamination, disruption of beneficial organisms, resistance development and food-safety concerns. Biological inputs provide an alternative or complementary strategy for improving crop production while reducing unnecessary dependence on synthetic agrochemicals. Biofertilizers contain beneficial microorganisms that improve nutrient availability through processes such as biological nitrogen fixation, phosphorus solubilization, potassium and zinc mobilization, sulfur transformation and production of plant-growth-promoting compounds. Biopesticides include microbial agents, plant extracts, biochemical substances, pheromones, insect growth regulators and plant-incorporated protectants. These products can suppress pests through competition, antibiosis, parasitism, infection, feeding deterrence, reproductive disruption or interference with insect development. The review shows that biological agricultural inputs are expanding globally and have considerable potential in Africa. Nigeria possesses substantial agricultural land, biodiversity and scientific capacity that could support locally adapted biological products. Nevertheless, adoption is constrained by inconsistent product quality, storage problems, limited farmer knowledge, regulatory challenges, variable field performance and the relatively slow action of some biopesticides. Biofertilizers and biopesticides should therefore be integrated with other sustainable practices rather than treated as universal replacements for synthetic inputs. Future progress will depend on improved microbial strains, stable formulations, rigorous field validation, quality assurance, farmer training, supportive regulation and carefully evaluated nanobiotechnology. Such integration could improve soil health, crop productivity, environmental protection and food security.

Introduction

Agriculture must simultaneously provide food, maintain soil productivity and respond to environmental pressures. Crop pathogens, declining soil fertility, land degradation and climate variability increasingly threaten production and food quality. Synthetic fertilizers and pesticides have played an important role in increasing productivity, but their intensive use can create unintended consequences. Chemical residues may affect organisms beyond the target pest, repeated pesticide exposure can select resistant populations, and intensive chemical management may alter soil biological communities (Chaudhary et al., 2024; Swaine et al., 2025; Zhou et al., 2025).

Sustainable agriculture seeks to maintain productivity while reducing avoidable environmental damage. One approach is to strengthen the biological processes already operating in agricultural ecosystems. Microorganisms associated with roots can fix nitrogen, mobilize nutrients, produce plant hormones and stimulate plant defenses. Other microorganisms can suppress insects and pathogens. Plant-derived compounds and behavioral chemicals can provide additional pest-management options.

Biofertilizers and biopesticides consequently have complementary functions. Biofertilizers primarily improve nutrient cycling and plant development, whereas biopesticides are principally used to manage harmful organisms. Some microorganisms, however, perform several functions simultaneously, such as nutrient mobilization, pathogen suppression and stimulation of plant defense (Adedayo et al., 2022; Kalam et al., 2020).

Biological inputs should not be assumed to be automatically safe or universally effective. Their performance depends on crop species, microbial strain, soil properties, environmental conditions, product formulation and application method. The most sustainable strategy is therefore integration: biological products can be combined with resistant varieties, good soil management, monitoring, cultural practices and carefully targeted chemical intervention when necessary.

This review examines the main types of biofertilizers and biopesticides, their mechanisms, agricultural applications, benefits and limitations, and their prospects for sustainable agriculture, with particular attention to African and Nigerian conditions.

Biofertilizers: concept and importance

Biofertilizers are preparations containing living or dormant microorganisms that improve plant nutrition and growth through biological processes. Rather than simply supplying nutrients in chemical form, these products stimulate microorganisms capable of transforming nutrients from unavailable or poorly available forms into forms that plants can utilize (Al-Zubade et al., 2021; Verma et al., 2020).

Important groups include nitrogen-fixing organisms, phosphorus-solubilizing microorganisms, potassium-solubilizing microbes, sulfur-transforming organisms, zinc-solubilizing microorganisms and plant-growth-promoting rhizobacteria. A single microbial strain may possess several of these traits.

Nitrogen-fixing organisms are especially valuable because atmospheric nitrogen is abundant but plants cannot normally use N_2 directly. Nitrogenase-containing microorganisms convert atmospheric nitrogen into biologically useful nitrogen compounds. These organisms can be free-living, symbiotic or associative (Ambechada & Umrania, 2024; Tarabulsi et al., 2024).

Phosphorus-solubilizing microorganisms improve access to phosphorus that is chemically fixed in soil. Bacteria such as Bacillus and Pseudomonas and fungi such as Aspergillus and Trichoderma can produce organic acids and phosphatases that mobilize phosphorus (Etesami et al., 2021).

Potassium-solubilizing microorganisms release potassium from mineral sources, while sulfur-transforming organisms regulate sulfur oxidation and reduction. Zinc-solubilizing microbes can increase Zn availability through acidification, chelation and mineral transformation (Basak et al., 2022; Ladohia et al., 2024).

The importance of biofertilizers therefore extends beyond replacing a bag of chemical fertilizer. They support nutrient cycling, microbial activity and plant–microbe interactions. When properly selected, they may improve fertilizer-use efficiency and contribute to long-term soil health. Their effectiveness, however, depends strongly on environmental conditions and the ability of the inoculant to establish and function in the target soil.

Nitrogen fixation and plant-growth-promoting bacteria

Biological nitrogen fixation is a major microbial contribution to crop nutrition. Specialized microorganisms use nitrogenase enzymes to convert atmospheric nitrogen into ammonia, which enters biological nitrogen cycles. Nitrogen-fixing bacteria may be free-living, symbiotic or associated with plant roots (Mitter et al., 2021).

Azotobacter is a free-living nitrogen-fixing bacterium that can inhabit the rhizosphere of many crops. Besides nitrogen fixation, some strains produce growth-promoting substances, support root development and contribute to mineral acquisition. They may also produce compounds with activity against some soil pathogens (Ansar & Tangkesalu, 2023; Chaudhary et al., 2022). Rhizobium and related bacteria form symbiotic associations mainly with legumes. They enter roots and develop nodules where nitrogen fixation occurs. Genera such as Bradyrhizobium and Sinorhizobium have important roles in agricultural nitrogen supply and can reduce dependence on manufactured nitrogen fertilizers (Raza et al., 2020; Kumar et al., 2020). Azospirillum is commonly associated with cereals and other crops. It can influence root development through plant-growth-regulating substances and may improve tolerance to drought and other stresses (Ashraf et al., 2020; Goel & Singh, 2025).

Plant-growth-promoting rhizobacteria can also produce auxins, cytokinins, gibberellins, siderophores and ACC deaminase. These activities can increase root development, improve nutrient acquisition and help plants respond to stress. PGPR can additionally stimulate induced systemic resistance and suppress pathogens through competition or antimicrobial compounds (Kalam et al., 2020; Yang et al., 2024).

These benefits are influenced by soil pH, temperature, moisture, crop genotype and competition from native microorganisms. Therefore, the development of locally adapted strains and appropriate formulations is essential for reliable field performance.

Phosphorus, Potassium, Sulfur and Zinc Mobilization

Phosphorus is essential for energy transfer, nucleic acids, membranes and plant development. Although many soils contain substantial phosphorus, much of it is immobilized in mineral or organic forms. Phosphate-solubilizing bacteria and fungi can increase availability through organic-acid production, phosphatase activity and related mechanisms (Etesami et al., 2021; Kirui et al., 2022). Arbuscular mycorrhizal fungi provide another route for improving phosphorus acquisition. Their hyphae extend beyond the immediate root zone and explore soil that roots alone cannot efficiently exploit. Microbial phosphate mobilization can therefore complement mineral fertilizer management. Potassium is involved in osmotic regulation, stomatal control, enzyme activation, photosynthesis and stress tolerance. Much soil potassium is contained within minerals, and potassium-solubilizing microorganisms can release part of this reserve. Bacillus, Frateuria and other bacterial and fungal groups have been investigated for this purpose (Basak et al., 2022; Santosh et al., 2022).

Sulfur is required for amino acids, vitamins, enzymes and chlorophyll. Microorganisms regulate sulfur availability through mineralization, immobilization, oxidation and reduction. Sulfur-oxidizing bacteria can transform reduced sulfur compounds into sulfate, which is more readily available to plants (Wang et al., 2019; Malik et al., 2021). Zinc is required in relatively small amounts but is essential for enzymes, protein metabolism, chlorophyll formation and stress responses. Zinc-solubilizing bacteria can improve availability of poorly soluble Zn compounds through acidification, chelation and chemical transformation (Kushwaha et al., 2020; Ladohia et al., 2024). These microbial processes demonstrate that biofertilizers can improve the efficiency of nutrients already present in soil. Their use may reduce nutrient losses and complement mineral fertilizers, but results depend on microbial strain, soil chemistry, crop type and environmental conditions. Biofertilizers Classification and their roles in Plant Growth are shown in Table 1.

Soil Health and Rhizosphere Interactions

The rhizosphere is a biologically active zone where roots interact with microorganisms, minerals and organic matter. Beneficial bacteria such as Bacillus, Pseudomonas, Rhizobium and related groups can influence nutrient cycling, root development and plant defense. These interactions help determine plant performance and soil biological functioning (Adedayo et al., 2022; Kalam et al., 2020). Figure 1 shows the application of Algae as biofertilizers for maintenance of crop productivity and soil health.

PGPR may synthesize plant hormones that stimulate root branching and shoot development. Some produce siderophores that influence iron availability, while others produce enzymes such as ACC deaminase that can reduce stress-associated ethylene effects. Microorganisms can also release antimicrobial substances or compete with pathogens for nutrients and colonization sites.

The benefits are not limited to direct plant growth. Microbial inoculants can alter nutrient transformations and support soil biological activity. Biofertilizers may contribute to soil structure and fertility over time, particularly when incorporated into broader organic and biological management systems (Mącik et al., 2020; Samantaray et al., 2024).

The interaction between introduced microorganisms and native soil communities is nevertheless complex. A strain that performs well in a laboratory may fail to establish in a field because of temperature, moisture, pH, nutrient availability or competition. Crop genotype also influences the microbial community associated with roots.

For this reason, sustainable biofertilizer development should emphasize field-adapted microorganisms and multi-location testing. Local microbial resources may be particularly valuable in Africa because strains originating from regional soils may be better adapted to local environmental conditions. Biofertilizers can contribute to remediation of polluted soils. Microorganisms can transform contaminants and modify their availability, while healthier plants may tolerate environmental stress more effectively (Gaylarde & da Fonseca, 2025). This creates a link between soil fertility management and environmental restoration.

Biopesticides and Their Major Categories

Biopesticides are pest-control products derived from microorganisms, plants, animals or naturally occurring biochemical substances. Their diversity includes microbial pesticides, plant-incorporated protectants, botanical products, pheromones and insect growth regulators (Kumar et al., 2021; Daraban et al., 2023). Microbial pesticides use bacteria, fungi, viruses, protozoa or algae to suppress target organisms. Bacillus thuringiensis is a well-known bacterial example. Its insecticidal proteins become active in susceptible insect guts and damage intestinal cells, eventually causing death.

Fungal biopesticides such as Beauveria bassiana and Metarhizium species can infect insects after contacting their cuticle. Trichoderma and other beneficial fungi can suppress plant pathogens through competition, antibiosis, parasitism and stimulation of plant defense (Adeleke et al., 2022). Plant-incorporated protectants involve crops engineered to express pesticidal molecules. Bt cotton and Bt maize are prominent examples. They can reduce external insecticide applications, although resistance management and environmental assessment remain necessary.

Biochemical pesticides include plant extracts, essential oils, pheromones, fatty acids and insect growth regulators. Their action may involve repellence, feeding inhibition, reproductive interference or disruption of insect development. Such products can provide modes of action different from conventional neurotoxic insecticides. Biopesticides are best used as components of integrated pest management. Monitoring, resistant varieties, crop sanitation, crop rotation and biological control can reduce pest populations while limiting unnecessary pesticide applications (Adeleke et al., 2022). The suitability of a biological product depends on the target pest, crop, environmental conditions and timing of application.

Natural origin should not be equated with complete safety. Botanical compounds and microbial products can affect non-target organisms, and environmental risks must be assessed. Quality control is also important because biological products may vary in viability or active-compound concentration (Adeleke et al., 2022).

Microbial Biopesticides: Mechanisms and Applications

Microbial pesticides suppress pests through infection, toxicity, competition or other biological interactions. Their mechanisms differ according to the organism involved. Bacillus thuringiensis produces crystalline proteins during sporulation. When susceptible insect larvae ingest these proteins, the alkaline gut environment releases active toxins. These bind to receptors on intestinal cells and disrupt membrane integrity, eventually causing leakage, tissue damage and death (Hezakiel et al., 2024).

Entomopathogenic fungi act through a different route. Spores attach to an insect surface, germinate and penetrate the cuticle. Once inside, fungal growth and metabolites can overwhelm the host. Beauveria bassiana and Metarhizium anisopliae are important examples. Their effectiveness is influenced by humidity, temperature, formulation and host susceptibility. Trichoderma and other beneficial fungi can control plant pathogens through several mechanisms. They may compete for space and nutrients, produce antimicrobial compounds, parasitize pathogen structures or activate plant defense. Such multifunctionality makes microbial biocontrol attractive for sustainable crop protection. Formulation is critical for microbial products. Drying, encapsulation, emulsification and other technologies can improve storage stability and protect microorganisms during transport and application (De Oliveira et al., 2021). Poor storage can reduce microbial viability and lead to weak field performance.

Highly specific agents such as some baculoviruses can reduce risks to non-target organisms, although specificity can also limit the range of pests controlled. Continuous monitoring is therefore necessary to confirm efficacy and environmental safety (Nor et al., 2025). Microbial biopesticides are most effective when used preventively or as part of integrated pest management. Farmers need to understand the appropriate crop stage, environmental conditions and application method. Their slower action compared with some synthetic pesticides can be addressed through monitoring and early application rather than waiting for severe pest outbreaks.

Botanicals, Essential Oils and Semiochemicals

Plant-derived pesticides use extracts, oils or purified compounds from plants with biological activity against pests. Plants naturally produce alkaloids, terpenoids, phenolics, steroids and other secondary metabolites that can affect insects and pathogens (Ayilara et al., 2023). Botanical compounds may repel insects, inhibit feeding, interfere with respiration, disrupt development or affect reproduction. Neem is a widely studied example, while pyrethrins, nicotine, rotenone, sabadilla and quassia illustrate other plant-derived pest-control chemistries. Their natural origin does not remove the need for safety assessment because some botanical compounds can harm beneficial insects or other organisms.

Essential oils are mixtures of volatile plant compounds that may possess insecticidal, repellent and antifungal properties. Their activity depends on plant species, extraction method, concentration and target organism. Plant extracts have also been reported to suppress fungal pathogens such as Botrytis and Fusarium species (Kursa et al., 2022; Qessaoui et al., 2023). Pheromones provide a different strategy because they manipulate pest behavior rather than directly poisoning the organism. Synthetic pheromones can be used for monitoring, mass trapping and mating disruption. In mating disruption, pheromone signals interfere with the ability of males to locate females, thereby reducing successful reproduction (Reddy et al., 2020). Insect growth regulators interfere with normal development. Juvenile-hormone analogues and compounds that disrupt chitin formation can prevent immature insects from reaching adulthood. These products can be valuable where particular developmental stages are vulnerable (Reddy et al., 2020). The major advantage of these approaches is the availability of additional, often more targeted, modes of pest management. Their limitations include variability in plant chemical composition, short persistence of some products, formulation difficulties and the need for standardized active ingredients. Effective use therefore requires quality control and integration with other pest-management measures. The roles of Bio pesticides in Controlling Insect Pests are represented in Table 2.

Nano-Biopesticides and Technological Innovation

Nanotechnology is being investigated as a way to improve the delivery and stability of biological and biochemical pest-control products. Nano-biopesticides may consist of nanoscale materials with pesticidal properties or carriers that deliver active compounds more efficiently (Abdollahdokht et al., 2022).

Nanostructured formulations can potentially improve solubility, adhesion, stability and controlled release. These properties may be useful for plant extracts and microbial metabolites that otherwise degrade quickly. Green synthesis approaches, in which biological materials participate in nanoparticle production, are especially relevant to environmentally oriented research. Silver and copper nanoparticles have been investigated for pest and pathogen suppression, while zinc oxide, boron and silica nanoparticles have also been examined in agricultural applications (AbdElAziz et al., 2021; Ahmadian et al., 2021). Such materials may function as pesticides, nutrient carriers or stress-management tools.

Despite this promise, nanoparticles introduce new environmental questions. Their small size and high surface activity can influence soil microbes, plants, water systems and non-target organisms. Therefore, nanobiotechnology should not be assumed to be environmentally safe simply because it reduces conventional pesticide use. Environmental fate, persistence, dose-response relationships and non-target effects require careful investigation (Abdollahdokht et al., 2022).. For developing agricultural systems, the most promising direction may be combining nanotechnology with biological products rather than simply replacing synthetic pesticides with nanoparticles. Controlled-release carriers could improve the delivery of microbial metabolites, essential oils or other natural compounds. Cost and accessibility must also be considered. Technologies designed for smallholder agriculture should be scalable and affordable, with manufacturing and regulatory systems capable of ensuring consistent quality. Research institutions, private companies and farmers should be involved in product development so that laboratory innovations are translated into practical solutions. A comparative review on the roles of biofertilizers and biopesticides are shown in Table 3.

Integrating Biofertilizers and Biopesticides

Biofertilizers and biopesticides address different agricultural problems but can contribute to a common sustainability strategy. Biofertilizers improve nutrient cycling and plant development, whereas biopesticides reduce pest pressure. A healthy, well-nourished plant may also have greater capacity to withstand environmental stress. PGPR are particularly promising because individual strains can combine growth promotion, nutrient mobilization and disease suppression. Bacillus and Pseudomonas species, for example, may produce growth-promoting compounds, mobilize nutrients and stimulate plant defense (Kalam et al., 2020). Integrated use must nevertheless consider compatibility. A chemical or biological treatment designed to suppress a pathogen may also affect a beneficial microorganism. Fertilizer salts, pH and irrigation conditions can influence microbial survival. Consequently, mixtures should be tested before being recommended to farmers.

Table 1: Biofertilizers Classification and their roles in Plant Growth

Types of biofertilizers	Role in plant growth	Type of plants	Reference
Rhizobium	Enhanced nitrogen fixation and nutrient content	Beans	Daniel *et al.*,2022
Azotobacter and Phosphate Solubilizing Bacteria	Improve Growth and Yield Parameters	Tomatoes	Burungale *et al.*,2025
Bacillus subtilis, Pseudomonas fluorescens	Induced systemic response that reduced the stress	Tomato	Chaudhary *et al.*,2022
Azotobacter and *Bacillus sp*	Promote growth by fixing Nitrogen in the soil	Maize	Azeem *et al.*,2022
Leclercia adecarboxylata	Production of siderophores and Zinc solubilization	Cucumber	Kang *et al.*,2021
Trichoderma longibrachiatum and *Bacillus megaterium*	improved the seed germination	Soybean	Bakhshandeh *et al.*, 2020
Bacillus strains	Act against Verticillium wilt caused by *Verticillium dahliae*	Cotton	Hasan *et al.*,2020
Pantoea disper-sa, Pseudomonas fragi, P. agglomerans, Rhizobium spp. And *Enterobacter cloacae*	Improved the solubilization of zinc	Wheat	Yadav *et al.*,2023
B. aryabhattai ZM31, B. subtilis ZM63	Enhanced Zn uptake in plant	Maize	Sethi *et al.*,2025
Bacillus HL3RS14	Produce IAA, Glycine betaine and Proline that increased weight of roots and shoots	Maize	Mukhtar *et al.*,2020
Bradyrhizobium. japonicum SAY3-7 *B. elkanii* BLY3-8 and *S.griseoflavus* P4	Effective in increasing the shoot and root for growth and development	Mung bean, Cowpea, and Soybean	Chakraborty and Akhtar, 2021
Streptomyces spp.	Increased in plant biomass	Soybean	Sethi *et al.*,2025
Pseudomonas spp. VBZ4	Increased in number of fruits per plant	Tomato	Sethi *et al.*,2025

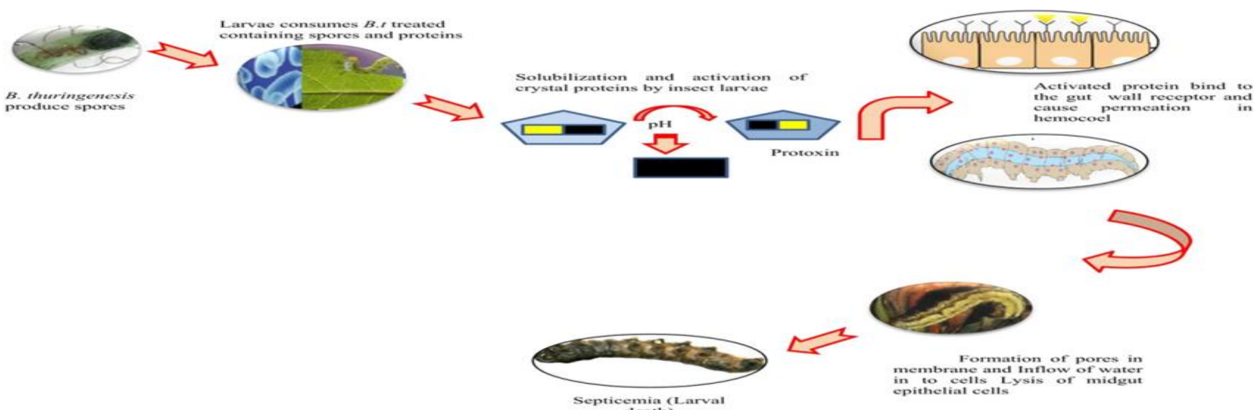

Figure 1. Algae as biofertilizers for maintenance of crop productivity and soil health (Ammar *et al.*,2023).

Table 2: Roles of Bio pesticides in Controlling Insect Pests

Category	Types of biopesticides	Role in plant protection	Host plants	Reference
Plant incorporated protestant	*Bacillus thuringiensis*	Resistant against Bollworms	Cotton	Nagaraj *et al.*,2024
	Bacillus thuringiensis	Reduce pest infestation in a variety of plants	Potato and Cabbage	Samada and Tambunan, 2020
Microbial biopesticides	*Trichoderma koningii*	Enhanced proline content and pathogen-related enzymes and inhibit the growth of pathogens	Tabacco	Taha *et al.*,2021
	Beauveria bassiana	Act as insecticide against Whitefly	Edible and Ornamental plant	McGuire and Northfield, 2020
	MaB-flocs *Nannochloropsis oculata*	Enhance fruit quality by increasing sugar and carotenoid content	Tomato	De Silva & Gnanavelrajah, 2025
	Extract of *Marrubium vulgare, Moringa oleifera, Psidium guajava* and *Casimiroa*	Antifungal activity against Botrytis cinerea	Tomato	Qessaoui *et al.*,2023
	Azadirachtin	effective against termites, grasshopper, leafhopper, beetles, cockroaches and moths and butterflies	Various crops	Toundou *et al.*,2022
	Extracts of *Lantana camara, Commiphora swynnertonii* and *Chrysanthemum cinerariifolium*	Manage disease	Common beans	Mkindi *et al.*,2020
	Quillaja saponaria	Nematicide against parasitic Nematodes in plants	Orchards, Vineyards, Field crops, Turf and	Guerra and Sepúlveda, 2020

			Ornamentals plants	
	Capsicum frutescens	Act against *Bemisia tabaci*	Tomato	Bharti *et al.*,2020
	Extract of *Chromolaena odorata*, *Morinda lucida*, *Azadirachta indica*, and *Ludwigia decurrens*	Significantly reduced *Aphtona* spp. attacked on okra	Okra	Toundou *et al.*,2020
	Pheromone	Monitoring and trapping of *Oryctes rhinoceros*, CRB	Coconut and Oil palms	Paudel *at al.,* 2023
	sweet and sour bait traps and pheromone traps	Traps against fall army worms	Maize	TRAN *et al.,* 2025
	Insect Growth Regulators Lufenuron, Pyriproxyfen, Buprofezin, Novaluron, and Flubendiamide	Act against melon fruit fly (Bactrocera cucurbitae)	Cucurbitaceous Vegetables	Kainat *et al.*,2025
	Insect Growth Regulators Cyromazine, methoprene	Cause mortality in houseflies *(Musca domestica* L)	Crops	Erdoğan, 2025
Nano pesticides	AgNPs	effective against the fungus (*Bipolaris sorokiniana)* the causative agent of spot blotch	Pumpkins, Cucumbers, and Wheat	dos Santos *et al.*,2024
	Ag and Cu NPs	Control damaging bruchids (weevils)	Beans and Leguminous seeds	Hemalatha *et al.*,2024
	ZnO	Improved crop yields and quality in terms of carbohydrate, protein, crude lipid and N, P, K and Zn	soya bean and wheat	AbdElAziz *et al.*,2021
	B NPs , Zn NPs, SiO_2 NPs	enhancing their growth	Wheat	Ahmadian *et al.*,2021

Table 3: Comparative Summary

Parameter	Biofertilizers	Biopesticides
Primary Action	Enhance soil fertility and promote plant growth by supplying or mobilizing nutrients.	Suppress or kill harmful organisms (insects, fungi, nematodes, weeds, etc.) that damage crops.
Mechanism of Action	Through nitrogen fixation, phosphate solubilization, hormone production, and enhancement of soil microbiota.	Through antibiosis, parasitism, toxin production, enzyme secretion, or competition for nutrients and space.
Key Agents	Bacteria, fungi, cyanobacteria	Bacteria, fungi, plant extracts
Environmental Impact	Non-toxic, improves soil structure and fertility over time.	Environmentally safe, reduces chemical pesticide residues and pest resistance.
Target	Soil and plant nutrient systems (roots, rhizosphere).	Pathogenic organisms — insects, fungi, bacteria, nematodes, or weeds.
End Result	Promotes plant growth and higher yield.	Provides crop protection and reduced pest population.

The soil microbiome is another important consideration. Agricultural chemicals can alter microbial communities, and biological inputs can also change microbial composition and function. Evaluating these changes can help determine whether an intervention improves soil health over the longer term (Swaine et al., 2025). The strongest approach is therefore integrated management. Farmers can combine biological inputs with resistant varieties, crop rotation, sanitation, monitoring, irrigation management and targeted chemical applications. Precision agriculture could improve this further by directing treatments to areas or crop stages where they are most needed. Biofertilizers may also contribute to remediation of degraded or contaminated soils. Microorganisms can transform pollutants, modify nutrient availability and improve plant tolerance. This suggests that biological agricultural technologies can potentially connect food production with environmental restoration.

Successful integration depends on evidence rather than assumptions. Field trials should evaluate crop yield, nutrient-use efficiency, pest suppression, soil health, economic return and environmental effects. Long-term trials are particularly important because some microbial benefits may develop gradually.

Africa and Nigeria: Opportunities for Bioinput Development

Africa has substantial potential for biological agricultural technologies because of its diverse ecosystems, agricultural land and microbial resources. At the same time, many farming systems face fertilizer costs, soil degradation, pest pressure and limited access to high-quality agricultural inputs. Biological technologies could address some of these constraints if products are adapted to local conditions.

Nigeria has a history of biofertilizer research and development, including inoculants for legumes. Nevertheless, adoption remains relatively limited, and the sector continues to face technical and commercial constraints (Raimi et al., 2021). Local production is potentially advantageous. Microbial strains selected from regional soils may be well adapted to local environmental conditions. Domestic formulation and manufacturing could also reduce dependence on imported products and improve access. Biopesticide development can similarly draw on local biodiversity. Plant extracts, entomopathogenic fungi and microbial agents have already been investigated against agricultural pests in Nigeria and other African countries. These resources could provide candidates for environmentally oriented crop protection.

However, commercialization requires rigorous quality control. Microorganisms must be correctly identified, products must contain appropriate concentrations, and efficacy and non-target safety should be demonstrated. Shelf-life and storage requirements must also be established.

Farmer confidence is another key issue. Biological products may perform differently from synthetic chemicals, and farmers need practical guidance on application timing, storage and compatibility. Demonstration farms and extension programs can help translate research findings into practical recommendations. A coordinated national strategy could connect universities, research institutes, biotechnology organizations, private manufacturers and farmer groups. Shared microbial collections, quality-control facilities and field-testing networks would reduce duplication and improve product reliability.

Nigeria's agricultural biodiversity and scientific capacity provide a foundation for development of locally appropriate biofertilizers and biopesticides. Realizing this potential will require investment in research, commercialization, regulation, farmer training and quality assurance.

Benefits and Challenges of Biological Inputs

Biofertilizers can improve nutrient-use efficiency, support root development, stimulate beneficial microbial activity and reduce dependence on some synthetic fertilizers. Biopesticides can provide targeted pest suppression, new modes of action and opportunities to reduce broad-spectrum chemical use. Together they can support more biologically based farming systems (Daniel et al., 2022; Ayilara et al., 2023).

However, biological inputs have limitations. Their performance may vary with temperature, moisture, pH, soil type, crop genotype and native microbial communities. A strain that performs strongly under controlled conditions may be less effective in a field environment.

Storage is another challenge. Living microorganisms can lose viability if exposed to unsuitable temperatures or moisture. Botanical products can also lose activity during storage because volatile or active compounds degrade.

Some biopesticides act more slowly than synthetic pesticides. Farmers facing severe pest outbreaks may therefore prefer rapid chemical products. Biological control is often more effective when applied preventively and combined with monitoring.

Quality control is fundamental. Poorly identified microorganisms, low viable counts, contamination, unstable formulations or variable concentrations can produce inconsistent results. Such problems can reduce farmer confidence and damage the reputation of biological products generally.

Training is equally important. Farmers need clear instructions on product preparation, dose, timing, storage and compatibility. Extension systems can help communicate these recommendations.

Regulation should ensure product identity, efficacy, environmental safety and labeling while avoiding unnecessary barriers to innovation. Harmonized regulatory frameworks can support commercialization and movement of validated products.

Several strategic responses are proposed icluding: improvement of stress-tolerant strains, development of stable formulations, extensive field testing, use of nanobiotechnology where appropriate, stronger regulation, financial incentives and strict quality assurance. These measures should be developed together because technical effectiveness alone does not guarantee agricultural adoption.

Conclusion

Biofertilizers and biopesticides provide important opportunities for developing more sustainable agricultural systems. Biofertilizers improve nutrient cycling through nitrogen fixation, phosphorus solubilization, potassium and zinc mobilization, sulfur transformation and plant-growth promotion. Biopesticides broaden pest-management options through microbial agents, botanicals, biochemical compounds, pheromones, insect growth regulators and plant-incorporated protectants.

Their value is greatest when they are integrated into wider agricultural management rather than treated as universal replacements for synthetic inputs. Effectiveness depends on strain quality, formulation, crop, soil, climate, pest biology and application practices. Reliable products therefore require rigorous testing, quality assurance, appropriate regulation and farmer training.

Africa, particularly Nigeria, has significant potential to develop biological inputs from local microbial and plant resources. Realizing this opportunity requires investment in research, formulation, field validation, manufacturing, extension and regulatory systems. Locally adapted technologies could improve nutrient-use efficiency, reduce some environmental pressures and strengthen agricultural resilience.

Future progress should focus on multifunctional microorganisms, stable formulations, soil-microbiome research, precision application and carefully evaluated nanobiotechnology. Long-term studies should assess productivity, soil health, environmental safety and economic performance together.

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