BSN BIOTECHNOLOGY SOCIETY OF NEPAL ESTD: 2007

Nepal Journal of Biotechnology

Publisher: Biotechnology Society of Nepal ISSN (Online): 2467-9313
Journal Homepage: https://nepjb.com/index.php/NJB ISSN (Print): 2091-1130

NJB NEPAL JOURNAL OF BIOTECHNOLOGY SINCE 2011

Harnessing Biofertilizers for Sustainable Agriculture: Mechanistic Insights, Performance Variability, and Soil Health Outcomes

Muhammad Junaid, Umair Anwar, Ajay Kumar, Hafsa Farooq, Isha Eman, Nizakat Hussain, Hafiza Rumaisa Zubair, Saqlain Shabbir

Institute of Biological Sciences, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Punjab, Pakistan

Received: 23 Nov 2025; Revised: 25 Dec 2025; Accepted: 27 Dec 2025; Published online: 31 Dec 2025

Abstract

The world is expected to hit 9.7 billion people by 2050, and this puts more strain on agrifood production systems to enhance their productivity without sacrificing the health of the soil and the environment. Biofertilizers like those produced on the basis of useful microorganisms, like nitrogen fixing, phosphate solubilizers and plant growth-promoting bacteria have seemed like potential alternatives or supplements to chemical fertilizers. This role of these microorganisms increases nutrient level, promotes root growth due to the production of phytohormones and increases plant resistance towards abiotic stress, hence contributing to crop yield and soil fertility. Greenhouse and field research indicate that single-strain and multi-strain microbial inoculants including the Effective Microorganisms (EM) can be used to increase the microbial diversity in soil, boost organic matter content and enhance water retention. The resulting responses in yield may however differ significantly depending on the crop species, soil properties, climate and management procedures. Although promising, inadequate shelf life, variability of field performance, and regulatory barriers are some of the challenges, which limit the widespread application of biofertilizers. This review will critically analyze the mechanisms behind the work of biofertilizers, compare the yearly reported effects on crop yield and soil health under different agricultural settings, and mention the main shortcomings which influence the reliability of biofertilizers. Microbial encapsulation, Artificial Intelligence based data-driven optimization, and the use of genome editing tools like CRISPR to improve the stability, efficacy, and scalability of biofertilizer solutions to address sustainable agriculture are new concepts.

Keywords: Biofertilizers, Microorganisms, Sustainable Agriculture, Soil fertility, Crop productivity, Environmental sustainability.

Corresponding author, email: bite211107066@kfueit.edu.pk, bite211107086@kfueit.edu.pk

Introduction

The population of the world is expected to reach about 9.7 billion by 2050 [1] , with greater requirements on agricultural systems to provide adequate food, fibers, and bio-based materials and reducing environmental degradation [2]. Traditional farming models that require large amounts of inputs have led to high yields but the sustainability of them has increasingly become debatable because of soil erosion, dwindling biodiversity, lack of water, and increased emission of greenhouse gases [3]. These issues argue the necessity of agricultural policies that can finely balance between production and a healthy environment [4].

Sustainable agriculture has come up as an integrated approach to these pressures by incorporating these aspects: ecological integrity, economic viability and social equity [5]. The main idea of this strategy is the management of soil as a dynamic biological system so that nutrient cycles, structural stability and ecosystem functioning are controlled microbial processes [6]. Crop diversification, limited use of tillage, good use of water and use of biological inputs are some of the practices that are highly regarded as being important elements of sustainable production systems [7]. In spite of such inventions, there are still instances where continued use of synthetic fertilizers and pesticides is compromising soil health and the quality of the environment in many agroecosystems [8].

Biofertilizers have raised growing concerns amid other biological inputs as a supplement to traditional fertilization [9]. Biofertilizers include the beneficial microorganisms that improve plant growth by increasing nutrient availability, physical growth, and biological activity of soil through biological fixation of nitrogen, solubilization of phosphorus, and growth-regulating compounds [10]. Biofertilizers contrast with the chemical fertilizers that simply introduce nutrients to the plant roots and frequently with ineffective processes resulting in reduced nutrient use efficiency and additional soil functioning, as biofertilizers bind with plant roots and the native soil microbiota [11].

The development of biofertilizers has been investigated on a large variety of microbial groups, such as nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, mycorrhizal fungi and plant growth promoting rhizobacteria [12]. These organisms not only affect the crop performance through the relevant improvement in nutrient uptake but also through the increase in stress tolerance and the establishment of soil microbial communities [13]. Responses to the application of biofertilizers are also reported as different among studies due to the difference in the crop species, soil properties, microbial formulations, and agronomic management practices [14]. Other than yield-related responses, biofertilizers have also been linked to changes in the soil structure, microbial diversity, and also lowering the loss of nutrients implying their wider applications to agroecosystem sustainability [15].

Understanding the growing literature, biofertilizers continue to be context-specific with regard to their effectiveness and in performance, the application generally lacks consistency in field conditions [16]. Differences in experimental designs, trial duration and evaluation criteria restrict comparisons between studies [17]. Moreover, there are still issues pertaining to the stability of the formulation, reliability in the field, adoption by the farmers, and regulatory measures that limit the use on large scale [18]. Recent developments promising to include multi-strain microbial consortia and novel formulation technologies have not been synthesized in agronomic and ecological sets [19].

In this regard, there is need to critically and integratively evaluate the available research. The synthesis of the existing data on biofertilizers is performed through the analysis of the underlying mechanism of these fertilizers, comparison of the reported effects on the crop yield and soil health, and finding of sources of variability and methodological limitation among the studies [20]. This review will offer clarity to gaps in knowledge, and emergent challenges, by explicitly addressing knowledge gaps and emerging challenges and outline future research and applications of biofertilizers in sustainable agricultural systems.

Review Methodology

This is a review article that is based on a systematic narrative framework to integrate the recent studies on biofertilizers in sustainable agriculture. Web of Science, Scopus, PubMed, and Google Scholar were used to retrieve peer-reviewed articles published in 2022-2025 using relevant keywords regarding biofertilizers, plant microbe interactions, soil health, and crop productivity. The initial screening highlighted about 300 articles with 148 studies being chosen to conduct a thorough review since it is relevant to agronomic outcomes and mechanistic knowledge.

The inclusion criteria were that the studies had to present a well-defined experimental, field-based or mechanistic evidence. Articles which were mainly promotional or which had insufficient methodological detail were eliminated. Qualitative study quality was measured by evaluating clearness of experimental design, suitability of parameters measured, and relevance with available literature as opposed to having a formal scoring system.

The literature chosen was then sorted into themes to allow comparative analyses of the crops, microbial formulations and the experimental conditions. Where incompatibilities occurred in the results, these were explained in the view of the variable in the soil properties, crop variety, and the purpose of the study and are addressed to point out the variance, shortcomings of the study and gaps in knowledge.

Classification and Mode of Action of Biofertilizers

Biofertilizers Containing Nitrogen-Fixing Microorganisms and Their Mechanisms

Nitrogen is available abundantly in the atmosphere that cannot be taken by most plants since they cannot decompose the molecular nitrogen through their roots [21]. This limitation is overcome by nitrogen-fixing biofertilizers that transform the atmospheric nitrogen into ammonia using nitrogenase enzyme complex [22]. It facilitates the availability of nitrogen to plants and decreases the use of synthetic nitrogen fertilizers [23].

Symbiotic and free-living bacteria are nitrogen-sustaining microorganisms. Leguminous crops have close associations with Symbiotic bacteria, including the *Rhizobium* species, which have a mutual relationship with the plants, with nitrogen fixation in root nodules in exchange of plant-derived carbon compounds [24]. These symbioses usually result in increased nitrogen inputs compared to non-symbiotic but have host-specificity [25]. Conversely, associative and free-living nitrogen fixing bacteria such as *Azotobacter* and *Azospirillum* can colonize a greater variety of crops, and increase nitrogen levels via associative interactions and not the specialized structures [26].

In addition to fixation of nitrogen, most diazotrophic biofertilizers affect plant growth by synthesizing phytohormones, such as auxins and gibberellins, which promote root growth and improvement of nutrient uptake [27]. Cyanobacteria as *Anabaena* and *Nostoc* have a role in total photosynthetic activity, organic matter, and

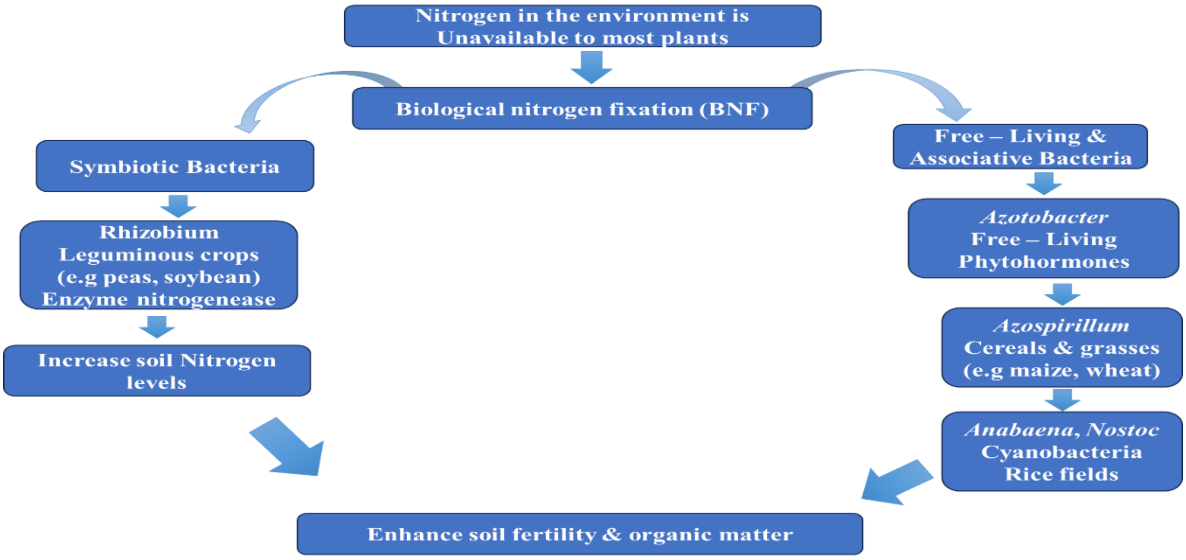

Figure 1. Overview of nitrogen-fixing biofertilizers illustrating symbiotic and free-living microbial pathways involved in biological nitrogen fixation and plant nitrogen uptake. (Figure created by the authors based on published literature.)

soil aggregation, in the flood system or semi-aquatic system of crop production [28].

Comparatively relative symbiotic nitrogen-fixing systems are expected to be less variable in nitrogen inputs when compared to free-living and associative bacteria which can be more generalized in applications, and variable in the field conditions [29]. Their functionality highly depends on the soil pH, availability of organic matters, the presence of oxygen and competition with the native microorganisms [30]. These aspects demonstrate the significance of environmental background in defining the efficiency of biofertilizers with nitrogen-fixing properties and complexity to site-specific application models [31].

Biofertilizers Containing Phosphate-Solubilizing Microorganisms and Their Mechanisms

Most of the phosphorus exists in the soil in insoluble forms and therefore inaccessible to plants, yet this phosphorus is vital in enabling plant root growth and energy transfer [32]. Some of the phosphate-solubilizing biofertilizers (PSBs), which eliminate this challenge, are *Bacillus, Pseudomonas,* and *Aspergillus*, as they release organic acids like gluconic, citric, and oxalic acid [33]. These acids convert the insoluble phosphates to soluble Molecules that plants can absorb, as it chelates cations and lowers acidity of the soil [34]. The problem of fixation

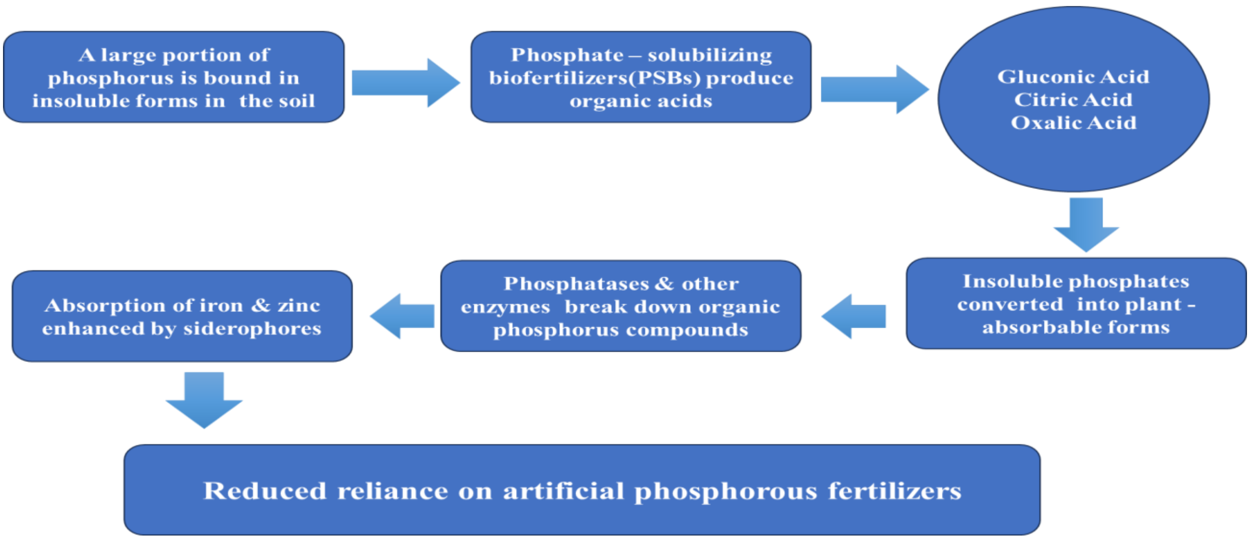

Figure 2. Mechanisms of phosphorus solubilization by biofertilizer microorganisms, highlighting organic acid production and enzymatic processes that enhance phosphorus availability to plants. (Figure created by the authors based on published literature.)

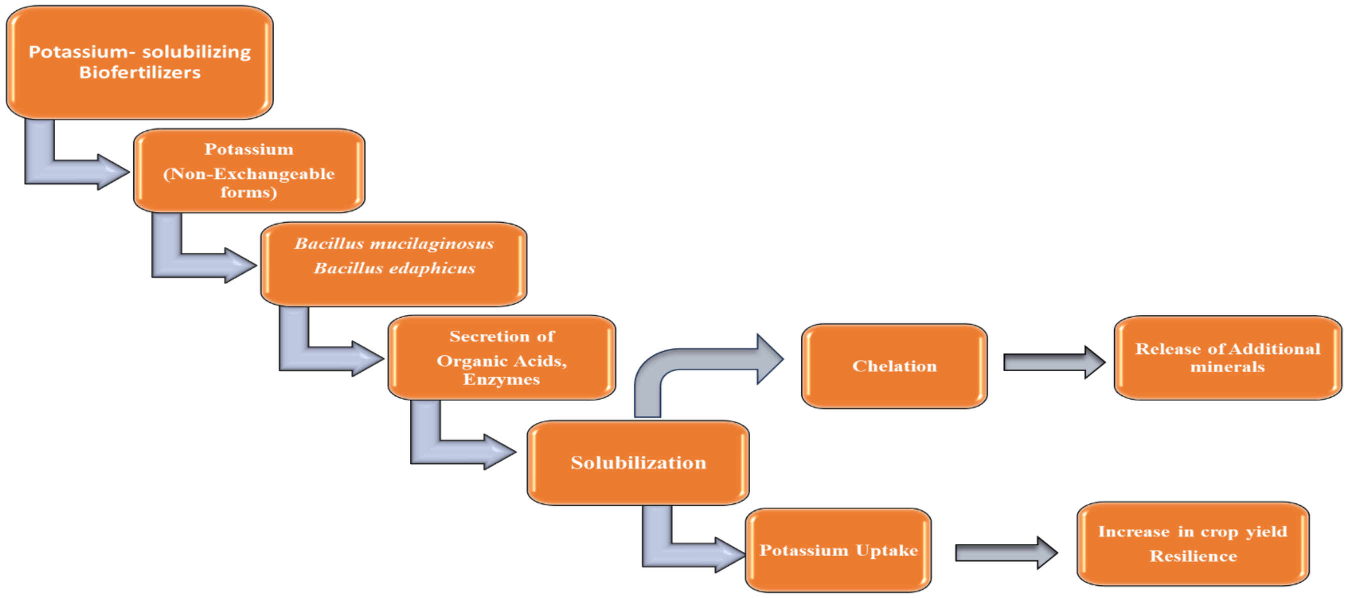

Figure 3. Potassium-solubilizing biofertilizer mechanisms showing microbial mineral dissolution processes that increase plant-available potassium in soil. (Figure created by the authors based on published literature.)

is common in both acid and alkaline soils but in this process of solubilizing nutrients, the availability of phosphorus is enhanced [35]. The PSBs also produce phosphatases and other enzymes which facilitate in the decomposition of organic phosphorus compounds [36].

Just like phosphorus, these microorganisms i.e. *Bacillus, Pseudomonas, Aspergillus* facilitate the absorption of iron and zinc that boost the overall nutrition of the plants [37]. Biocontrol is achieved, as well, by protecting crops, through production of siderophores are iron-chelating compounds that limit the access of soil-borne diseases to iron, by some PSBs, such as *Pseudomonas fluorescens* [38]. PSBs promote the use of sustainable nutrient and bolster the presence of stronger roots via reducing the usage of chemical phosphorus fertilizers [39].

Phosphate solubilizing microorganisms are mostly useful in phosphorus-deficient and highly fixed soils but their activity reduces in soils with high available phosphorus [40]. PSBs have a greater effect on early root growth as compared to potassium-solubilizing bacteria, whilst KSBs directly affect the level of water regulation and stress resistance [41].

Biofertilizers Containing Potassium-Solubilizing Microorganisms and Their Mechanisms

Potassium, abundant in soils, is important in water management, enzyme activation and protection against disease [42]. Potassium Solubilizing Bacteria (KSBs) include *Bacillus mucilaginosus* and *Bacillus edaphicus* which dissolve potassium by producing organic acids and enzymes to degrade mineral complexes [43].

In this mechanism of solubilization, the presence of potassium is much more absorbable by plants leading to a better productivity and plant strength [44]. The KSBs also enhance the fertility of soils when some mineral fertility such as iron and zinc are released through chelation [45]. By stimulating the availability of nutrients without requiring the use of any synthetic resources, such bacteria stimulate a hearty plant growth in diverse environmental conditions as well as contribute to sustainable soil management, particularly as far as low-potassium areas are concerned [46].

Mycorrhizal Fungi and Their Mechanisms of Action

Arbuscular mycorrhizal fungi (AMF) are made up of fungal genera like *Glomus, Acaulospora, Gigaspora* in which the AMF form a mutualism by colonizing the roots of plants and forming a highly branching fungal network that greatly enhances the nutrient uptake power of the root [47]. The AMF are very proficient in phosphorus mobilization owing to their ability to penetrate into the microspores of soil and access the insoluble phosphates, which are beyond the reach of roots [48].

They help each other by plants supplying the fungus with form of carbohydrates to sustain this symbiotic relationship [49]. AMF enhances drought tolerance due to increased water absorption besides augmenting phosphorus uptake and enhancing uptake of the micronutrients such as zinc and copper [50]. Also, this symbiosis promotes soil aggregations, reducing erosion and improving the structure [51]. AMF is the key to sustainable agriculture since it enhances the resilience of

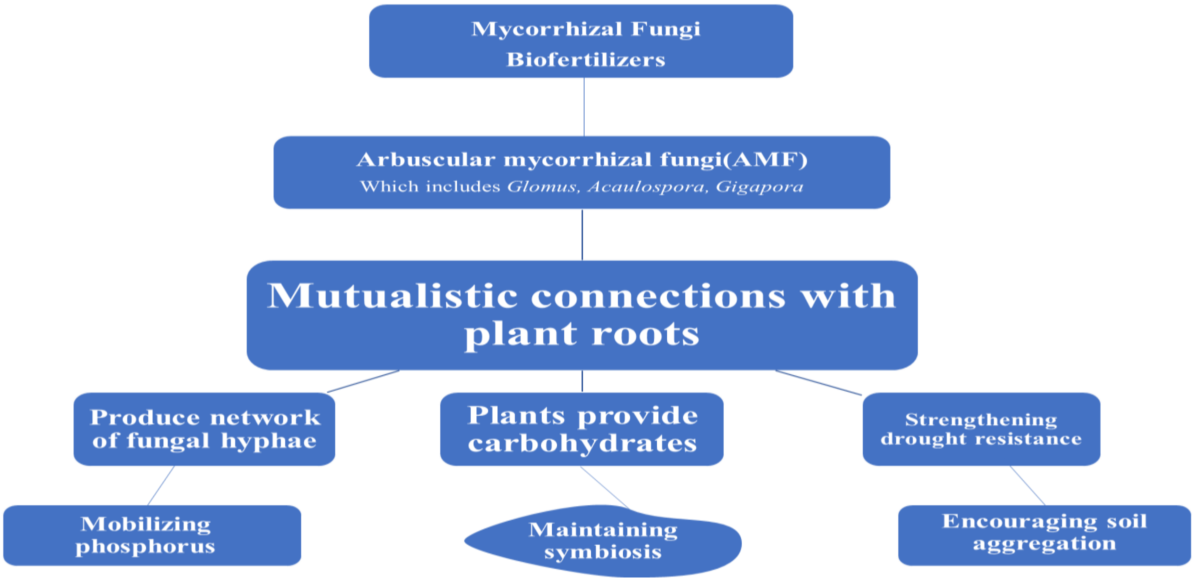

Figure 4. Mycorrhizal fungal associations with plant roots illustrating enhanced nutrient uptake, soil aggregation, and water acquisition pathways. (Figure created by the authors based on published literature.)

plants and serves as the natural continuation of the root system, eliminating the use of chemical fertilizers [52]. Even though AMF enhance nutrient absorption and stress resilience, they do not work well in highly intensively fertilized systems and when soils are commonly disturbed [53]. Host specificity and compatibility also determine the performance in the field, which hinders the use of homogenous response to a particular flowing system [54].

Cyanobacterial Biofertilizers and Their Mechanism of Action

The cyanobacteria including *Anabaena*, *Nostoc* and *Spirulina* can be used as biofertilizers because they can fix nitrogen in addition to performing photosynthesis and therefore, they best fit in the wetland crops like rice [55]. These microorganisms have the ability to take nitrogenous material out of the atmosphere and nitrogen is captured within specialized cells known as heterocysts which maintain the nitrogenase enzyme in conditions with a minimal amount of oxygen [56].

Cyanobacteria produce hormones in addition to nitrogen fixing namely hormones called auxins and cytokinins which facilitate growth of roots and shoots [57]. They cement soil particles with their gelatinous, polysaccharide rich exudates making their soil in formation more textural, better in water holding capacity and resistant to erosions [58]. Cyanobacteria contribute to the long-term well-being of soils with their contribution of organic-matter and the enrichment of microbial diversity in the rhizosphere, making them fundamental to effective rice cultivation [59].

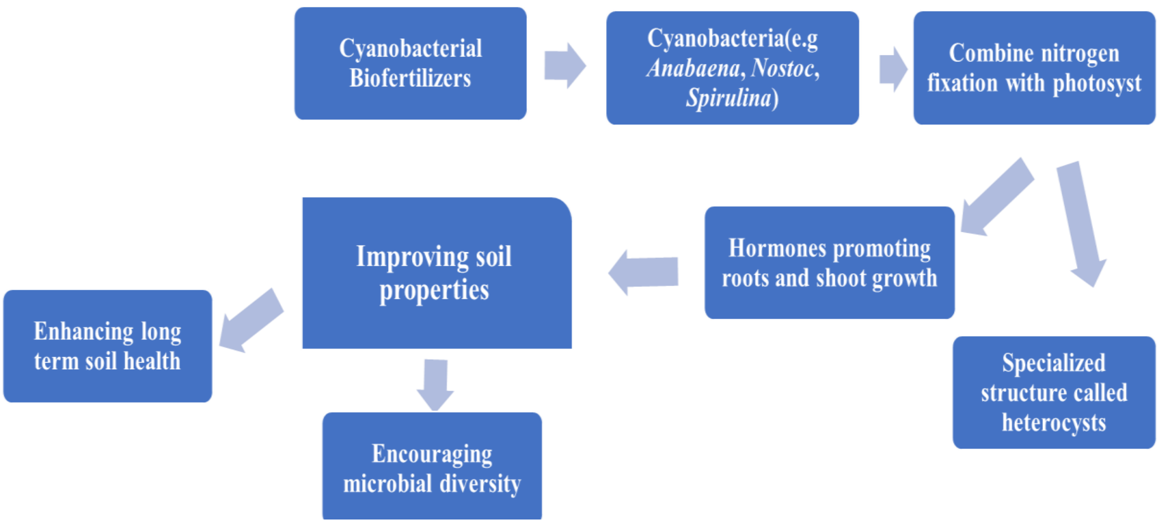

Figure 5. Functional mechanisms of cyanobacterial biofertilizers demonstrating nitrogen fixation, organic matter contribution, and soil conditioning in flooded agroecosystems. (Figure created by the authors based on published literature.)

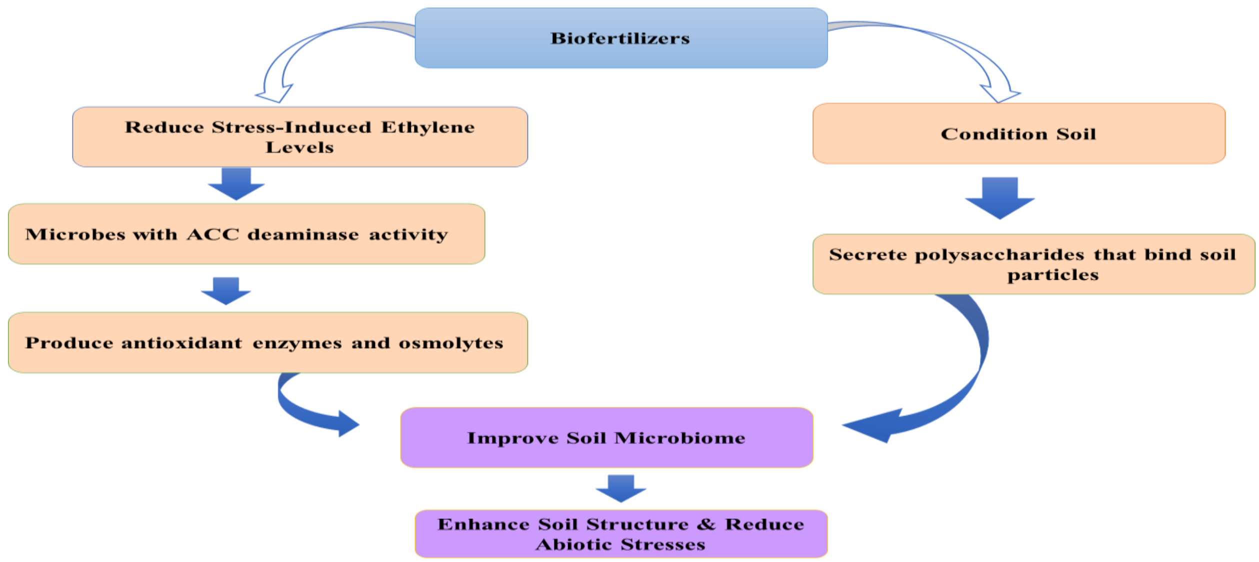

Figure 7. Biofertilizer-mediated stress tolerance and soil conditioning mechanisms contributing to improved plant resilience and soil structural stability. (Figure created by the authors based on published literature.)

Plant Growth-Promoting Rhizobacteria (PGPR) and Their Mechanisms of Action

Plant growth-promoting rhizobacteria (PGPR) such as *Enterobacter, Burkholderia* and *Pseudomonas* are versatile biofertilizers that in various ways improve the health of plants [60]. Other than fixing nitrogen and solubilizing phosphorus, the PGPR produce phytohormones like auxins, gibberellins and cytokinins which promote shoot growth, root growth and delayed senescence [61].

Also, by encouraging Induced systematic resistance (ISR), they enhance resiliency because plants are ready to cope with infection by synthesizing metabolites and innovative defenses [62]. In an example, Pseudomonas fluorescens comes in to facilitate the ISR against fungal infections [63]. As well, the PGPR produce siderophores,

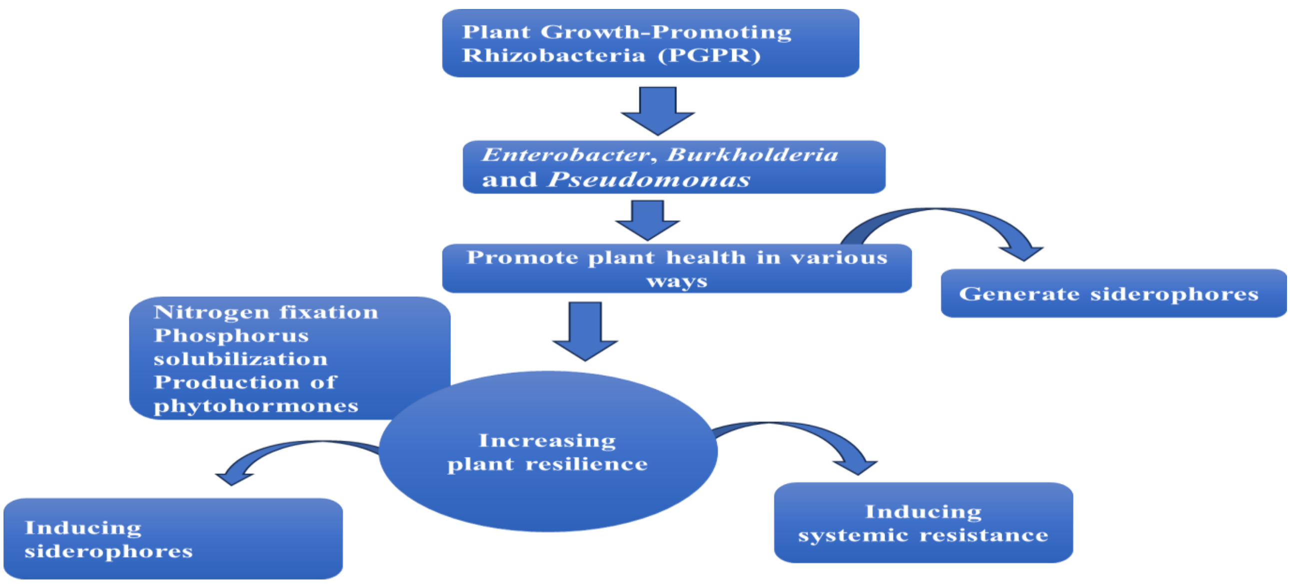

Figure 6. Key mechanisms of plant growth-promoting rhizobacteria (PGPR), including phytohormone production, nutrient mobilization, and induced systemic resistance. (Figure created by the authors based on published literature.)

that bind iron and release it to the plants denying the pathogens the essential mineral[64]. Moreover, some of the PGPR contain ACC (1-Aminocyclopropane-1-carboxylate) deaminase, a protein which assists plants to decrease ethylene content when the plants are in a state of stress e.g. drought, salt or heavy metal exposure [65]. These various efforts improve the crops and vegetation health along with soil health, which, makes PGPR, great partners in the fight towards sustainable agricultural practices [66].

The functionality of the PGPR is usually multifunctional in comparison to single-function biofertilizers; nevertheless, its effectiveness is mainly indirectly affected by the field conditions as they depend on the sensitivity to the physicochemical characteristics of soil as well as the competition of the microorganisms [67].

Stress Tolerance and Soil Conditioning Mechanisms

Biofertilizers are vital in helping plants to overcome the challenges of the environment in addition to promoting soil health [68]. Microbes that produce ethylene lowering effects can lead to plants thriving in heavy metal, salty or arid environments due to ACC deaminase activity that reduces ethylene levels thereby limiting stress effects which are associated with ethylene [69]. The other ones produce antioxidant enzymes and osmolytes which makes the plants more resistant than ever [70]. By the release of polysaccharides that bind the particles, cyanobacteria and other biofertilizers prepare soil use, which reduces erosion and improves the capture of water [71]. These bacteria have the power to enhance the microbiome of the soil leading to a healthy environment which is fertile on a long-term basis [72]. Biofertilizers strengthen an agricultural system and reduce environmental influences in the agricultural approach by boosting soil framework and reducing abiotic forces [73]. In general, indirect processes promoting stress reduction by biofertilizers can be divided into several processes, although the stability of these processes in fields depends greatly on environmental factors, microbial interactions, and agronomic practices [74].

Impact on Crop Yield and Soil Health

Biofertilizers are currently being studied as biologically based inputs that could improve the productivity of crops besides improving soil health [75]. These inoculants comprise useful microorganisms, such as nitrogen-fixing microorganisms, phosphate-solubilizing microorganisms and potassium-mobilizing fungi and these microorganisms affect plant growth by means of nutrient mobilization and rhizosphere interactions [76]. Biofertilizers are unlike other forms of conventional fertilizers in that they help in both short and long term yield response as well as the soil fertility as they interact with available biological processes in the soil [77].

Effects of Biofertilizers on Crop Productivity

Biofertilizer is very beneficial in crop production since they enhance plant toleration to abiotic stress, root growth, and nutrient absorption [78]. At the rhizosphere they stimulate microbe interactions, synthesize phytohormones and promote sustainable plant physiology [79]. They have been shown to be effective in a variety of staple crops, such as wheat, rice, maize, and legumes [80].

Wheat: Yield Enhancement and Nutrient Efficiency

When given biofertilizer, wheat has responded well. Wheat yields were improved by 10%–40% with *Azospirillum* species inoculation, which also improved plant height, spike count, and grain weight [81]. In addition to secreting growth-promoting chemicals that promote biomass formation, these bacteria improve nitrogen fixation. *Azotobacter* spp. enhance grain protein content by fixing nitrogen, contributing 20–40 kg of nitrogen per hectare per year [82]. The Ibaa99 wheat cultivar in Baghdad experienced a 62% increase in grain output, rising from 2.83 tons/ha to 4.58 tons/ha, following three foliar sprays of EM-1. In a separate field experiment, combining *Azotobacter* with cattle manure led to a 15% increase in yield [83].

Rice: Increased Yield and Nutritional Quality

Anabaena and the *Azolla–Anabaena* symbiosis are cyanobacteria that greatly aid rice farming, especially when the soil is nutrient-deficient or wet [84]. Increasing yields by 10–15%, these bacteria provide 20–40 kg N/ha/season [85]. When *Anabaena* variabilis and 50% nitrogen fertilizer were used in China, sheath blight was suppressed and yields increased by 13.9–22% [86]. In India, 16-year research found that integrating biofertilizers with Farmyard Manure (FYM) and crop wastes increased rice yields by 49.2% (from 3.08 to 4.59 tons/ha) with an increase in protein content of 9.6–10.7% and up to 81.9% more zinc and iron, rice quality also improved [87].

4.4 Maize: Productivity and Stress Tolerance

Particularly in deteriorated soils, biofertilizers such as *Bacillus, Pseudomonas*, and *Azospirillum brasilense* increased maize yields by 10–30% [88]. Shoot biomass increased in Brazil as a result of *Azospirillum*'s 40 kg/ha nitrogen contribution. PGPR mixes increased yields in Australia by as much as 15% [89]. Enhancing resistance to drought and salt through improved chlorophyll synthesis and antioxidant activity, the integration of nano-silica with *Azotobacter* and *Pseudomonas* increased maize yields [90].

Legumes: Optimizing Nitrogen Fixation

The nitrogen-fixing bacteria provide significant advantages to legumes such as soybean and pigeon pea [91]. By inoculating 78% of soybean fields with *Bradyrhizobium*, Brazil was able to meet all of its nitrogen requirements while saving 13 billion dollars a year [92]. The M1H inoculant, which contained *Serratia marcescens* and *PaeniBacillus polymyxa*, enhanced the helpful soil microorganisms *Mortierella* and *Cunninghamella* in pigeon pea, boosting biomass and creating a nourishing rhizosphere [93].

In crops, both yield responses to the application of biofertilizers are reported to vary significantly between crops due to changes in scale of the experiment, time of cropping, fertility status of the soil, and practices in place of application of biofertilizers [94]. A higher yield increment is frequently noticed in nutrient-hulled or degraded soils and under integrated systems of biofertilizers with organic amendments, but are smaller in systems of high input conventional regimes [95]. The research is founded on largely single season field experiments or localized research, which restricts comparative research and projection to the long-term dynamism of yields. These results emphasize the fact that biofertilizer performance varies according to the context, not in all settings [96].

Comparative Yield Performance

Table 1. Comparative yield responses of wheat, rice, maize, and legumes under biofertilizer-based fertilization strategies [97].

Crop	Treatment	Yield (tons/ha)	% Increase Over Control
Wheat	EM-1 (3 sprays)	4.58	~62%
Wheat	*Azotobacter* + Manure	3.36	+15%
Wheat	Chemical Nitrogen Only	3.56	+26%
Rice	A. variabilis + 50% Urea	7.90	+13.9–22%
Rice	FYM + Crop Residues + Biofertilizers	4.59	+49.2%
Maize	*Azospirillum brasilense*	11.5 (est.)	+15%
Maize	Nano-Si + *Azotobacter* + *Pseudomonas*	~11.5 (est.)	+10–15%
Soybean	*Bradyrhizobium* spp.	Meets 100% N	–
Pigeon Pea	M1H Inoculant	Significant	–

The comparative group yield data that has been summarized in Table 1 depict the level of variability in crop response to biofertilizer based interventions. The yields of wheat and rice usually exhibit a higher response to the use of biofertilizers when they are combined with organic or less chemical treatments, whereas maize yields are less strong and are often described as the results of field experiments. The reported outcomes differ as they indicate the variation in the soil fertility, climatic conditions, crop genotype and application strategy. In the cases where yield values are given as estimates the values are obtained based on reported ranges as opposed to standardized multi-location tests.

Soil Fertility Improvement

In addition to increasing crop output, biofertilizers improve the physical characteristics, microbial diversity, organic matter, nutrient dynamics, pH balance, and soil health.

Organic Matter and Soil Structure

Applying biofertilizers greatly increases soil organic carbon (SOC), particularly when combined with compost or FYM [98]. Better aeration, water retention, and root growth resulted with a 76.5% rise in SOC (from 4.9 g/kg to 8.6 g/kg) in long-term rice studies [99]. Plots of wheat treated with manure and *Azotobacter* showed better nutritional profiles and 15% higher biomass [100]. In rice fields, *Anabaena variabilis* also increased phosphorus and total organic carbon [101].

Microbial Diversity and Functionality

Biofertilizers introduce beneficial species including *Bacillus, Pseudomonas, Trichoderma*, and mycorrhizal fungi, which enhance the variety of soil microbes [102]. In pigeon pea, M1H suppressed pathogens such *Zopfiella* while increasing the prevalence of *Cunninghamella* and *Mortierella* [103]. The rhizosphere of maize was richer, as evidenced by the microbial diversity index rising from 3.96 (chemical) to 4.06 (biofertilized) [104].

.

Table 2: Rhizospheric microbial responses to biofertilizer application [105]

Microbial Genus	Effect of Biofertilizer
Mortierella	Increased
Bacillus	Increased
Zopfiella	Decreased
Podospora	Decreased

Alteration in Rhizospheric microbial composition after the application of biofertilizer is generally characterized by improvement in the abundance of useful genera including *Bacillus* and *Mortierella* and depletion in the abundance of some saprophytic fungi, summarized in Table 2.

The alteration of the Rhizospheric microbial composition is evidence that applying biofertilizer may selectively promote advantageous microbial groups and inhibit the potential pathogens [106]. These changes indicate positive functional diversity but these responses depend on crop species, soils and the original microbial community structure [107].

Nutrient Availability and Soil Chemistry

The availability of nitrogen (via *Azotobacter*, *Azospirillum*, and *Rhizobium*), phosphorus (through *Bacillus, Pseudomonas,* and *Aspergillus*), potassium, and zinc is increased by biofertilizers [108]. Nutrient-mobilizing enzymes and organic acids are released by these microorganisms. *Anabaena variabilis* raised the amount of nitrogen in rice crops [109]. Higher levels of accessible potassium and phosphorus were seen in maize when biofertilizer was used [110].

Soil pH and Electrical Conductivity

By stabilizing pH and lowering EC, biofertilizers promote root development and microbial viability [111]. *Anabaena* variabilis kept rice's pH in the range of 6.5 to 6.8 [112]. The biofertilized plots of maize had a pH of 6.86, whereas the controls had a pH of 6.76. By reducing EC by as much as 45.8%, nutrient absorption was improved [113].

Physical Soil Properties

Soil aggregation and porosity are enhanced by prolonged application. The following are noteworthy changes:

Table 3. Soil physical property changes with biofertilizer application [114]

Soil Property	Without Biofertilizer	With Biofertilizer	% Change
Water Holding Capacity (%)	36.4	56.7	+55.8%
Soil Moisture Content (%)	17.8	26.6	+49.3%
Bulk Density (Mg/m^3)	1.53	1.39	-9.2%
Organic Carbon (g/kg)	4.9	8.6	+76%

Enhanced physical characteristics of soil are indicative of increased soil aggregation and organic materials accretion with extended use of biofertilizers [115]. Although these transformations help increase the soil resiliency, decrease the risk of soil erosion, and ensure agricultural sustainability in the long term, the majority of the observations are based on long-term experimental plots, which underlines the necessity to repeat such transformations in the fields [116].

Challenges, Limitations, and Future Prospects in Biofertilizer Development

Current Limitations: Shelf Life, Formulation, and Farmer Awareness

Regardless of their known agronomic and environmental advantages, the broad-scale application of biofertilizers is still limited by a number of real constraints. The major difficulty is that of the relatively short shelf life of products that are founded on living microbial cells [117]. Phosphate-solubilizing fungi (e.g., *Aspergillus niger*, *Penicillium bilaiae*) and nitrogen-fixing bacteria (e.g., *Rhizobium, Azotobacter*, *Azospirillum*, etc.) are typical microorganisms used to produce biofertilizers; they are very delicate to varying environmental conditions (temperature, humidity, and light) [118]. Consequently, when storing, transporting and handling in the field, there are often decreases in microbial viability [119]. Equally, biofertilizers derived out of microalgae are under most times highly concentrated in terms of bioactive compounds, but they tend to lose their viability soon after being made into a useful biofertilizer, which restricts their practical use in the field [120].

Carrier materials are very important in preserving the survival of microbes [121]. Traditional hard carriers (peat or lignite) have a tendency not to maintain their microbial activity in the long term and can be easily contaminated [122]. Together with the advantages in handling, and shelf life, liquid formulations are exposed to the effects of storage-induced stresses, such as oxygen limitation, and degradation of nutrients [123]. Such difficulties are also made worse in the parsimonious and tropical areas where most of the time it is not feasible to observe the advocated storage conditions due to smallholder famers [124].

Another bottleneck is formulation technology. Carrier systems using cost-effective and biodegradable materials and the ability to maintain microbial viability is still a challenge to achieve [125]. The use of encapsulation with the help of different materials and types of materials like alginate or chitosan is promising, but the production cost and the challenge of scalability make it impossible to fully commercialize because of high costs and difficulties in scale [126]. Also, the quality of the carrier and strain-carrier interaction may cause variation in performance of the field, which impedes the trust of farmers in biofertilizer products [127].

In addition to formulation constraints, adoption is greatly limited by lack of awareness and technical knowledge among the farmers especially in the developing regions [128]. Lack of understanding of proper method of application and anticipated results is caused by inadequate extension services and inadequate training programs [129]. Thus, chemical fertilizer is usually considered more trusted since it has faster and noticeable action on the growth of crops but biofertilizer can show slow or fluctuating effect in the field. This is still the impression that is making biofertilizer-based inputs not fully embraced [130].

Regulatory and Adoption Challenges

A major obstacle to commercialization of the biofertilizer and its application is the issue of regulatory fragmentation [131]. Unlike chemical fertilizers biofertilizers lack regular tests, quality standards and labeling in various areas [132].

Biofertilizers have very inconsistent regulatory practices around the world. In a few places, biofertilizers are also under bio-stimulant or biopesticides and therefore creating confusion in registration and approval processes, with other nations having devised biofertilizer-specific laws [133]. Also, since there is no standardized way of determining microbial viability and field performance then one may not easily predict the efficacy of the product under different agroecological settings [134].

Biological variation also provides consumers with inconsistent results in the field. The native microbiota of soils, climatic conditions, soil pH and soil water and high temperature have a strong impact on the performance of introduced microbial strains [135]. The agronomic performance of inoculated strains is likely to exhibit inconsistency because of competition with native microorganisms, which lowers potential colonization in order to be successful. These uncertainties require carrying out a long-term, location-specific field experiment to address them and this is costly in monetary terms especially to small and medium scale manufacturers hence, delaying product validation and adoption [136].

Future Directions: Advanced Bioformulations, Intelligent Delivery, and Emerging Technologies

The recent developments in formulation science provide promising directions to overcome the major constraints that are attributed to biofertilizer. The next generation bioformulations are more aimed at enhancing the microbial stability and controlled release by developed encapsulation methods [137]. Biodegradable polymers or beads made of alginate or those made of biochar can facilitate the survival of microbes during storage and transportation and slow down gradual release into the rhizosphere [138]. These methods can enhance the reliability of products in a wide range of agroclimatic conditions, especially to the smallholder systems of farming.

Alternatives in the methods of delivery also demonstrate possibilities to enhance uniformity and effectiveness. Methods like coating of the seeds, using a hydrogel-based delivery method and having granular formulations have been explored which would help improve the microbial establishment and lessen the environmental stress when used [139]. The purposes of these methods are the maximization of plant interactions and the microbes and the reduction of field variability [140]. Nevertheless, cost efficiency, the ability to produce on large scale, and the compatibility with the current agricultural practice all remain conditions of large-scale implementation [141].

New technologies, such as synthetic microbial consortia and systems biology strategies, are also adding to a more sophisticated knowledge about the interaction of microbes in soil of plants [142]. Multi-omics data has also made possible rational development of microbial combinations that have complementary functional characteristics [143]. Though the strategies are promising in enhancing the nutrient availability and stress regulation, their functioning in the heterogeneous field environment needs further verification [144].

The use of digital technologies like artificial intelligence (AI) and the Internet of Things (IoT) platforms have become a popular topic in precision agriculture [37]. Even though these tools present the opportunities of using data in order to support the decisions, their direct usage as applied to biofertilizer optimization is not very common [145]. Difficulties in the availability of infrastructure, data quality and cost, and accessibility to users are some of the issues that impede high usage today, especially in low-resource agricultural systems [146]. Also, ethical issues, ownership of data, and economy-related aspects have to be considered before these technologies can be successfully incorporated into regular biofertilizer management [147]. Therefore, although technological innovations can be seen as a promising growth opportunity in the long-term, short-term development will probably become reliant on the enhancement of formulation strength, regulations, and cost-efficiency in comparison to the traditional chemical fertilizers [148].

Conclusion

Biofertilizers are a significant biological approach to the promotion of sustainable agriculture through the improvement of crop production and the maintenance of health and ecological operations of the soil. Biological fixation of nutrients, solubilization of nutrients, synthesis of phytohormones, and stimulation of nutrient-beneficial soil microbial communities, biofertilizers add to enhanced nutrient-use efficiency and soil long-term fertility. Instead of replacing synthetic treatments into all systems, they can be highly valued in integrated and low-input farming situations, where they can be used to supplement organic treatment and the minimization of chemical treatment.

Although they have been shown to be effective, the efficacy of biofertilizers is highly situational and varies according to soil characteristics, climate, type of crop cultivated, resistance to formulations, and the manner of application. The future studies should thus be more focused on the long and multi-location field tests, standardized assessment systems, and better mechanistic insights of the interaction between microbes and plants in the soil. The future is in formulation technologies and microbial consortia development and in using precision agricultural instruments that should facilitate consistency and scalability. All in all, a more rigorous and well-founded incorporation of biofertilizers with the system of agriculture will be crucial towards achieving the image of biofertilizers in the production of agriculture.

References

[1] O. Oluwole et al., “Sustainable transformation agenda for enhanced global food and nutrition security: a narrative review,” Front. Nutr., vol. 10, Aug. 2023, doi: 10.3389/fnut.2023.1226538.

[2] A. K. Priya, A. Alagumalai, D. Balaji, and H. Song, “Bio-based agricultural products: a sustainable alternative to agrochemicals for promoting a circular economy,” RSC Sustain., vol. 1, no. 4, pp. 746–762, 2023, doi: 10.1039/D3SU00075C.

[3] D.-C. Țopa, S. Căpșună, A.-E. Calistru, and C. Ailincăi, “Sustainable Practices for Enhancing Soil Health and Crop Quality in Modern Agriculture: A Review,” Agriculture, vol. 15, no. 9, p. 998, Jan. 2025, doi: 10.3390/agriculture15090998.

[4] C. Ononogbo et al., “Agricultural and environmental sustainability in nigeria: a review of challenges and possible eco-friendly remedies,” Environ. Dev. Sustain., Sept. 2024, doi: 10.1007/s10668-024-05435-2.

[5] D. Dönmez, M. A. Isak, T. İzgü, and Ö. Şimşek, “Green Horizons: Navigating the Future of Agriculture through Sustainable Practices,” Sustainability, vol. 16, no. 8, p. 3505, Jan. 2024, doi: 10.3390/su16083505.

[6] M. Hartmann and J. Six, “Soil structure and microbiome functions in agroecosystems,” Nat. Rev. Earth Environ., vol. 4, no. 1, pp. 4–18, Jan. 2023, doi: 10.1038/s43017-022-00366-w.

[7] P. B. Angon, N. Anjum, Mst. M. Akter, S. Kc, R. P. Suma, and S. Jannat, “An Overview of the Impact of Tillage and Cropping Systems on Soil Health in Agricultural Practices,” Adv. Agric., vol. 2023, no. 1, p. 8861216, 2023, doi: 10.1155/2023/8861216.

[8] I. Pergner and C. Lippert, “On the effects that motivate pesticide use in perspective of designing a cropping system without pesticides but with mineral fertilizer—a review,” Agron. Sustain. Dev., vol. 43, no. 2, p. 24, Feb. 2023, doi: 10.1007/s13593-023-00877-w.

[9] G. Mawlood, O. Al-Rubaie, M. Najm, Y. Sumuu, O. Asri, and A. Saadi, “Enhance the productivity of field crops through bio- and organic fertilization as a sustainable alternative to chemical fertilizers: A Comprehensive review,” Pharaonic J. Sci., vol. 1, no. 2, pp. 136–152, Aug. 2025, doi: 10.71428/PJS.2025.0204.

[10] A. Gupta, B. S. Saharan, P. K. Sadh, and J. S. Duhan, “Green to green: harnessing bio-fertilizers for sustainable pulse production and food security,” Discov. Plants, vol. 1, no. 1, p. 73, Dec. 2024, doi: 10.1007/s44372-024-00079-y.

[11] S. Figiel, P. Rusek, U. Ryszko, and M. S. Brodowska, “Microbially Enhanced Biofertilizers: Technologies, Mechanisms of Action, and Agricultural Applications,” Agronomy, vol. 15, no. 5, p. 1191, May 2025, doi: 10.3390/agronomy15051191.

[12] A. M. Timofeeva, M. R. Galyamova, and S. E. Sedykh, “Plant Growth-Promoting Soil Bacteria: Nitrogen Fixation, Phosphate Solubilization, Siderophore Production, and Other Biological Activities,” Plants, vol. 12, no. 24, p. 4074, Jan. 2023, doi: 10.3390/plants12244074.

[13] Q. Chen, Y. Song, Y. An, Y. Lu, and G. Zhong, “Soil Microorganisms: Their Role in Enhancing Crop Nutrition and Health,” Diversity, vol. 16, no. 12, p. 734, Dec. 2024, doi: 10.3390/d16120734.

[14] D. Shahwar et al., “Role of microbial inoculants as bio fertilizers for improving crop productivity: A review,” Heliyon, vol. 9, no. 6, June 2023, doi: 10.1016/j.heliyon.2023.e16134.

[15] G. Albahri et al., “Enhancing Essential Grains Yield for Sustainable Food Security and Bio-Safe Agriculture through Latest Innovative Approaches,” Agronomy, vol. 13, no. 7, p. 1709, July 2023, doi: 10.3390/agronomy13071709.

[16] J. Herrero, A. Ramírez-Santos, E. Díaz-Santos, and G. Torres-Cortés, “Biofertilizers for Enhanced Nitrogen Use Efficiency: Mechanisms, Innovations, and Challenges,” Nitrogen, vol. 6, no. 4, p. 111, Dec. 2025, doi: 10.3390/nitrogen6040111.

[17] A. S. Baharudin, N. Zainol, and N. H. Aziz, “Parameters evaluation for biofertilizer production from mushroom waste through design of experiment,” J. Environ. Manage., vol. 378, p. 124734, Apr. 2025, doi: 10.1016/j.jenvman.2025.124734.

[18] R. Dhillon and Q. Moncur, “Small-Scale Farming: A Review of Challenges and Potential Opportunities Offered by Technological Advancements,” Sustainability, vol. 15, no. 21, p. 15478, Jan. 2023, doi: 10.3390/su152115478.

[19] M. Singh, S. Jha, D. Pathak, and G. Maisnam, “Advancing biofertilizers: the evolution from single-strain formulations to synthetic microbial communities (SynCom) for sustainable agriculture,” Discov. Plants, vol. 2, no. 1, p. 226, July 2025, doi: 10.1007/s44372-025-00318-w.

[20] A. A. Naghdi, S. Piri, A. Khaligi, and P. Moradi, “Comparative Analysis of Biofertilizers and Chemical Fertilizers on Yield Components and Nitrate Accumulation in Sante Potato Cultivar,” J. Hum. Environ. Health Promot., vol. 11, no. 4, pp. 244–252, Oct. 2025, doi: 10.61882/jhehp.713.

[21] O. Zayed et al., “Nitrogen Journey in Plants: From Uptake to Metabolism, Stress Response, and Microbe Interaction,” Biomolecules, vol. 13, no. 10, p. 1443, Oct. 2023, doi: 10.3390/biom13101443.

[22] U. Kafeel, U. Jahan, and F. A. Khan, “Role of mineral nutrients in biological nitrogen fixation,” in Sustainable Plant Nutrition, Elsevier, 2023, pp. 87–106. doi: 10.1016/B978-0-443-18675-2.00004-3.

[23] P. Barłóg, W. Grzebisz, and R. Łukowiak, “Fertilizers and Fertilization Strategies Mitigating Soil Factors Constraining Efficiency of Nitrogen in Plant Production,” Plants, vol. 11, no. 14, p. 1855, Jan. 2022, doi: 10.3390/plants11141855.

[24] M. H. Abd-Alla, S. M. Al-Amri, and A.-W. E. El-Enany, “Enhancing Rhizobium–Legume Symbiosis and Reducing Nitrogen Fertilizer Use Are Potential Options for Mitigating Climate Change,” Agriculture, vol. 13, no. 11, p. 2092, Nov. 2023, doi: 10.3390/agriculture13112092.

[25] X. Yu and H. Zhu, “Enacting partner specificity in legume–rhizobia symbioses,” aBIOTECH, vol. 6, no. 2, pp. 311–327, June 2025, doi: 10.1007/s42994-024-00193-1.

[26] P. Sharma, S. Sangwan, H. Kaur, A. Patra, Anamika, and S. Mehta, “Diversity and Evolution of Nitrogen Fixing Bacteria,” in Sustainable Agriculture Reviews 60: Microbial Processes in Agriculture, N. K. Singh, A. Chattopadhyay, and E. Lichtfouse, Eds., Cham: Springer Nature Switzerland, 2023, pp. 95–120. doi: 10.1007/978-3-031-24181-9_5.

[27] P. Singh et al., “Nitrogen fixation and phytohormone stimulation of sugarcane plant through plant growth promoting diazotrophic Pseudomonas,” Biotechnol. Genet. Eng. Rev., vol. 40, no. 1, pp. 15–35, Jan. 2024, doi: 10.1080/02648725.2023.2177814.

[28] M. Wipplingerová, J. Pokorný, and J. Kaštovský, “Cyanobacteria and algae from Chýnov and Koněprusy caves (Czech Republic),” Int. J. Speleol., vol. 54, no. 1, p. ijs2514, Mar. 2025, doi: 10.5038/1827-806X.ijs2514.

[29] H. Dai et al., "Fertilization effects on symbiotic and free-living biological nitrogen fixations: Similar effects but different mechanisms," Appl. Soil Ecol., vol. 202, p. 105590, Oct. 2024, doi: 10.1016/j.apsoil.2024.105590.

[30] L. Philippot, C. Chenu, A. Kappler, M. C. Rillig, and N. Fierer, "The interplay between microbial communities and soil properties," Nat. Rev. Microbiol., vol. 22, no. 4, pp. 226–239, Apr. 2024, doi: 10.1038/s41579-023-00980-5.

[31] T. Nawaz, L. Gu, S. Fahad, S. Saud, B. Bleakley, and R. Zhou, "Exploring Sustainable Agriculture with Nitrogen-Fixing Cyanobacteria and Nanotechnology," Molecules, vol. 29, no. 11, p. 2534, Jan. 2024, doi: 10.3390/molecules29112534.

[32] M. Ibrahim, M. Iqbal, Y.-T. Tang, S. Khan, D.-X. Guan, and G. Li, "Phosphorus Mobilization in Plant–Soil Environments and Inspired Strategies for Managing Phosphorus: A Review," Agronomy, vol. 12, no. 10, p. 2539, Oct. 2022, doi: 10.3390/agronomy12102539.

[33] R. Sarmah and A. K. Sarma, "Phosphate Solubilizing Microorganisms: A Review," Commun. Soil Sci. Plant Anal., vol. 54, no. 10, pp. 1306–1315, May 2023, doi: 10.1080/00103624.2022.2142238.

[34] R. Mitra, P. Yadav, K. Usha, and B. Singh, "Regulatory role of organic acids and phytochelators in influencing the rhizospheric availability of phosphorus and iron and their uptake by plants," Plant Physiol. Rep., vol. 27, no. 2, pp. 193–206, June 2022, doi: 10.1007/s40502-022-00650-3.

[35] M. Adnan, S. Fahad, M. H. Saleem, and R. Lal, "Sustainable phosphorus management in calcareous soils: problems and prospects," J. Plant Nutr., vol. 48, no. 13, pp. 2179–2200, Aug. 2025, doi: 10.1080/01904167.2025.2477269.

[36] L. Pan and B. Cai, "Phosphate-Solubilizing Bacteria: Advances in Their Physiology, Molecular Mechanisms and Microbial Community Effects," Microorganisms, vol. 11, no. 12, p. 2904, Dec. 2023, doi: 10.3390/microorganisms11122904.

[37] A. Jalal, E. F. Júnior, and M. C. M. Teixeira Filho, "Interaction of Zinc Mineral Nutrition and Plant Growth-Promoting Bacteria in Tropical Agricultural Systems: A Review," Plants, vol. 13, no. 5, p. 571, Jan. 2024, doi: 10.3390/plants13050571.

[38] P. Saranraj et al., "Plant Growth-Promoting and Biocontrol Metabolites Produced by Endophytic Pseudomonas fluorescence," in Secondary Metabolites and Volatiles of PGPR in Plant-Growth Promotion, R. Z. Sayyed and V. G. Uarrota, Eds., Cham: Springer International Publishing, 2022, pp. 349–381. doi: 10.1007/978-3-031-07559-9_18.

[39] N. Khan, M. H. Siddiqui, S. Ahmad, M. M. Ahmad, and S. Siddiqui, "New Insights in Enhancing the Phosphorus Use Efficiency using Phosphate-Solubilizing Microorganisms and Their Role in Cropping System," Geomicrobiol. J., vol. 41, no. 5, pp. 485–495, May 2024, doi: 10.1080/01490451.2024.2331111.

[40] E. V. Ramos Cabrera, Z. Y. Delgado Espinosa, and A. F. Solis Pino, "Use of Phosphorus-Solubilizing Microorganisms as a Biotechnological Alternative: A Review," Microorganisms, vol. 12, no. 8, p. 1591, Aug. 2024, doi: 10.3390/microorganisms12081591.

[41] A. Oraee, A. Tehranifar, and S. Karimpour, "Possibility of Producing Tulip Bulblet Under Drought Stress Using Potassium and Phosphorus Solubilizing Bacteria," Commun. Soil Sci. Plant Anal., vol. 54, no. 6, pp. 819–835, Mar. 2023, doi: 10.1080/00103624.2022.2130935.

[42] C. C. Ortel, T. L. Roberts, and J. C. Rupe, "A review of the interaction between potassium nutrition and plant disease control," Agrosystems Geosci. Environ., vol. 7, no. 2, p. e20489, 2024, doi: 10.1002/agg2.20489.

[43] S. K. Vishwakarma et al., "*Bacillus* spp.: Nature's Gift to Agriculture and Humankind," in Applications of *Bacillus* and *Bacillus* Derived Genera in Agriculture, Biotechnology and Beyond, V. Mageshwaran, U. B. Singh, A. K. Saxena, and H. B. Singh, Eds., Singapore: Springer Nature, 2024, pp. 1–36. doi: 10.1007/978-981-99-8195-3_1.

[44] L. I. da Silva, M. C. Pereira, A. M. X. de Carvalho, V. H. Buttrós, M. Pasqual, and J. Dória, "Phosphorus-Solubilizing Microorganisms: A Key to Sustainable Agriculture," Agriculture, vol. 13, no. 2, p. 462, Feb. 2023, doi: 10.3390/agriculture13020462.

[45] G. Sethi et al., "Enhancing soil health and crop productivity: the role of zinc-solubilizing bacteria in sustainable agriculture," Plant Growth Regul., vol. 105, no. 3, pp. 601–617, June 2025, doi: 10.1007/s10725-025-01294-7.

[46] H. N. Onyeaka, A. A. Akinsemolu, K. F. Siyanbola, and V. A. Adetunji, "Green Microbe Profile: Rhizophagus intraradices—A Review of Benevolent Fungi Promoting Plant Health and Sustainability," Microbiol. Res., vol. 15, no. 2, pp. 1028–1049, June 2024, doi: 10.3390/microbiolres15020068.

[47] R. Ouhaddou, M. Anli, R. Ben-Laouane, A. Boutasknit, M. Baslam, and A. Meddich, "The Importance of the Glomus Genus as a Potential Candidate for Sustainable Agriculture Under Arid Environments: A Review," Int. J. Plant Biol., vol. 16, no. 1, p. 32, Mar. 2025, doi: 10.3390/ijpb16010032.

[48] R. Liu and Y. Chen, "Mycorrhizal Symbiosis: Evolution, Opportunities, Challenges, and Prospects," in Arbuscular Mycorrhizal Fungi in Sustainable Agriculture: Inoculum Production and Application, M. Parihar, A. Rakshit, A. Adholeya, and Y. Chen, Eds., Singapore: Springer Nature, 2024, pp. 1–35. doi: 10.1007/978-981-97-0296-1_1.

[49] S. Qi et al., "Arbuscular Mycorrhizal Fungi Contribute to Phosphorous Uptake and Allocation Strategies of Solidago canadensis in a Phosphorous-Deficient Environment," Front. Plant Sci., vol. 13, Mar. 2022, doi: 10.3389/fpls.2022.831654.

[50] H. Tang et al., "The Critical Role of Arbuscular Mycorrhizal Fungi to Improve Drought Tolerance and Nitrogen Use Efficiency in Crops," Front. Plant Sci., vol. 13, July 2022, doi: 10.3389/fpls.2022.919166.

[51] B. Valenzuela-Aragon, M. Cardinale, E. Rolli, L. Rustioni, and D. Francioli, "The role of arbuscular mycorrhizal fungi in abiotic stress management in viticulture under climatic shifts," Plant Stress, vol. 16, p. 100863, June 2025, doi: 10.1016/j.stress.2025.100863.

[52] W. Sun and M. H. Shahrajabian, "The Application of Arbuscular Mycorrhizal Fungi as Microbial Biostimulant, Sustainable Approaches in Modern Agriculture," Plants, vol. 12, no. 17, p. 3101, Jan. 2023, doi: 10.3390/plants12173101.

[53] W. Nie et al., "Arbuscular Mycorrhizal Fungi: Boosting Crop Resilience to Environmental Stresses," Microorganisms, vol. 12, no. 12, p. 2448, Dec. 2024, doi: 10.3390/microorganisms12122448.

[54] H. Tang et al., "The Critical Role of Arbuscular Mycorrhizal Fungi to Improve Drought Tolerance and Nitrogen Use Efficiency in Crops," Front. Plant Sci., vol. 13, July 2022, doi: 10.3389/fpls.2022.919166.

[55] M. Shamina, "A Review on Cyanobacterial Biofertilizer for Organic Rice Cultivation: Technology, Improvement and Future Prospects," Int. J. Algae, vol. 24, no. 1, 2022, doi: 10.1615/InterJAlgae.v24.i1.60.

[56] S. Pandey, R. Soni, P. Devi, and A. Pandey, "The Study of Heterocystous and Non-Heterocystous Nitrogen Fixing Cyanobacteria: Prospects for the Future," 2023.

[57] S. Uniyal, M. Bhandari, P. Singh, R. K. Singh, and S. P. Tiwari, "Cytokinin biosynthesis in cyanobacteria: Insights for crop improvement," Front. Genet., vol. 13, Sept. 2022, doi: 10.3389/fgene.2022.933226.

[58] T. Nawaz, S. Saud, L. Gu, I. Khan, S. Fahad, and R. Zhou, "Cyanobacteria: Harnessing the power of microorganisms for plant growth promotion, stress alleviation, and phytoremediation in the era of sustainable agriculture," Plant Stress, vol. 11, p. 100399, Mar. 2024, doi: 10.1016/j.stress.2024.100399.

[59] W. Solomon, L. Mutum, M. Rakszegi, T. Janda, and Z. Molnár, "Harnessing the Synergy of the Cyanobacteria-Plant Growth Promoting Bacteria for Improved Maize (Zea mays) Growth and Soil Health," Sustainability, vol. 15, no. 24, p. 16660, Jan. 2023, doi: 10.3390/su152416660.

[60] B. N. Aloo, V. Tripathi, B. A. Makumba, and E. R. Mbega, "Plant growth-promoting rhizobacterial biofertilizers for crop production: The past, present, and future," Front. Plant Sci., vol. 13, Sept. 2022, doi: 10.3389/fpls.2022.1002448.

[61] A. EL Sabagh et al., "Phytohormones as Growth Regulators During Abiotic Stress Tolerance in Plants," Front. Agron., vol. 4, Mar. 2022, doi: 10.3389/fagro.2022.765068.

[62] Y. Yu, Y. Gui, Z. Li, C. Jiang, J. Guo, and D. Niu, "Induced Systemic Resistance for Improving Plant Immunity by Beneficial Microbes," Plants, vol. 11, no. 3, p. 386, Jan. 2022, doi: 10.3390/plants11030386.
[63] A. Rabari et al., "Articulating beneficial rhizobacteria-mediated plant defenses through induced systemic resistance: A review," Pedosphere, vol. 33, no. 4, pp. 556–566, Aug. 2023, doi: 10.1016/j.pedsph.2022.10.003.
[64] A. Syed, A. M. Elgorban, A. H. Bahkali, R. Eswaramoorthy, R. K. Iqbal, and S. Danish, "Metal-tolerant and siderophore producing Pseudomonas fluorescence and Trichoderma spp. improved the growth, biochemical features and yield attributes of chickpea by lowering Cd uptake," Sci. Rep., vol. 13, no. 1, p. 4471, Mar. 2023, doi: 10.1038/s41598-023-31330-3.
[65] A. Gupta et al., "ACC Deaminase Produced by PGPR Mitigates the Adverse Effect of Osmotic and Salinity Stresses in Pisum sativum through Modulating the Antioxidants Activities," Plants, vol. 11, no. 24, p. 3419, Jan. 2022, doi: 10.3390/plants11243419.
[66] A. Gupta, K. Singh, M. Charles, and N. Pathak, "role of acc deaminase producing plant growth promoting rhizobacteria in ameliorating the salinity stress conditions: a review," Eras J. Med. Res., vol. 9, no. 1, pp. 60–77, June 2022, doi: 10.24041/ejmr2022.09.
[67] Y. Liang, M. Zhang, B. Peng, X. Zeng, X. Li, and J. Wei, "Impact of fermented rapeseed cake mixed *Bacillus* velezensis on the bacterial community structure and cultivation of tobacco cultivar K326," Sci. Rep., vol. 15, no. 1, p. 24818, July 2025, doi: 10.1038/s41598-025-08400-9.
[68] A. Ortiz and E. Sansinenea, "The Role of Beneficial Microorganisms in Soil Quality and Plant Health," Sustainability, vol. 14, no. 9, p. 5358, Jan. 2022, doi: 10.3390/su14095358.
[69] S. Chandwani and N. Amaresan, "Role of ACC deaminase producing bacteria for abiotic stress management and sustainable agriculture production," Environ. Sci. Pollut. Res., vol. 29, no. 16, pp. 22843–22859, Apr. 2022, doi: 10.1007/s11356-022-18745-7.
[70] Ma. D. C. Orozco-Mosqueda, B. R. Glick, and G. Santoyo, "ACC deaminase in plant growth-promoting bacteria (PGPB): An efficient mechanism to counter salt stress in crops," Microbiol. Res., vol. 235, p. 126439, May 2020, doi: 10.1016/j.micres.2020.126439.
[71] Z. Abideen et al., "Algal-Mediated Nanoparticles, Phycochar, and Biofertilizers for Mitigating Abiotic Stresses in Plants: A Review," Agronomy, vol. 12, no. 8, p. 1788, Aug. 2022, doi: 10.3390/agronomy12081788.
[72] S. Bibi, I. Saadaoui, A. Bibi, M. Al-Ghouti, and M. H. Abu-Dieyeh, "Applications, advancements, and challenges of cyanobacteria-based biofertilizers for sustainable agro and ecosystems in arid climates," Bioresour. Technol. Rep., vol. 25, p. 101789, Feb. 2024, doi: 10.1016/j.biteb.2024.101789.
[73] F. Masmoudi et al., "Halobacteria-Based Biofertilizers: A Promising Alternative for Enhancing Soil Fertility and Crop Productivity under Biotic and Abiotic Stresses—A Review," Microorganisms, vol. 11, no. 5, p. 1248, May 2023, doi: 10.3390/microorganisms11051248.
[74] S. Figiel, P. Rusek, U. Ryszko, and M. S. Brodowska, "Microbially Enhanced Biofertilizers: Technologies, Mechanisms of Action, and Agricultural Applications," Agronomy, vol. 15, no. 5, p. 1191, May 2025, doi: 10.3390/agronomy15051191.
[75] A. Kurniawati, G. Toth, K. Ylivainio, and Z. Toth, "Opportunities and challenges of bio-based fertilizers utilization for improving soil health," Org. Agric., vol. 13, no. 3, pp. 335–350, Sept. 2023, doi: 10.1007/s13165-023-00432-7.
[76] G. Tamiru, "Role of Bio-Fertilizers in Improving Soil Fertility and Crop Production," Cross Curr. Int. J. Agric. Vet. Sci., vol. 5, no. 06, pp. 118–127, Dec. 2023, doi: 10.36344/ccijavs.2023.v05i06.003.
[77] S. Singh et al., "Soil fertility management: Role of organic amendments and bio-fertilizers: A review," Int. J. Res. Agron., vol. 7, no. 12, pp. 766–772, 2024, doi: 10.33545/2618060X.2024.v7.i12j.2253.
[78] F. Masmoudi et al., "Halobacteria-Based Biofertilizers: A Promising Alternative for Enhancing Soil Fertility and Crop Productivity under Biotic and Abiotic Stresses—A Review," Microorganisms, vol. 11, no. 5, p. 1248, May 2023, doi: 10.3390/microorganisms11051248.
[79] F. Jamil, H. Mukhtar, M. Fouillaud, and L. Dufossé, "Rhizosphere Signaling: Insights into Plant–Rhizomicrobiome Interactions for Sustainable Agronomy," Microorganisms, vol. 10, no. 5, p. 899, May 2022, doi: 10.3390/microorganisms10050899.
[80] Q. Chen, Y. Song, Y. An, Y. Lu, and G. Zhong, "Mechanisms and Impact of Rhizosphere Microbial Metabolites on Crop Health, Traits, Functional Components: A Comprehensive Review," Molecules, vol. 29, no. 24, p. 5922, Jan. 2024, doi: 10.3390/molecules29245922.
[81] Z. Khaliq, S. Mukhtar, M. Zareen, S. Mehnaz, and K. A. Malik, "Comparison of application method of PGPR-based biofertilizer on wheat (Triticum aestivum L.) growth under climate control and field conditions," Pak. J. Bot., vol. 56, no. 4, Aug. 2024, doi: 10.30848/PJB2024-4(11).
[82] M. Rafique et al., "Unlocking the potential of biofilm-forming plant growth-promoting rhizobacteria for growth and yield enhancement in wheat (Triticum aestivum L.)," Sci. Rep., vol. 14, no. 1, p. 15546, July 2024, doi: 10.1038/s41598-024-66562-4.
[83] A. M. H. Al-Shammari and A. H. Noaema, "Response of some Bread Wheat Cultivars to Foliar Feeding Stages with Nano-Microelements," IOP Conf. Ser. Earth Environ. Sci., vol. 1225, no. 1, p. 012082, Aug. 2023, doi: 10.1088/1755-1315/1225/1/012082.
[84] W. S. Kabato, N. Hailegnaw, T. E. Chaffamo, A. Samuel, A. G. S. D. De Silva, and Z. Molnár, "Microalgae-Based Strategies for Soil Health and Crop Productivity: Mechanisms, Challenges, and Pathways to Climate-Resilient Agriculture," Agronomy, vol. 15, no. 11, p. 2669, Nov. 2025, doi: 10.3390/agronomy15112669.
[85] S. Bocchi and A. Malgioglio, "Azolla-Anabaena as a Biofertilizer for Rice Paddy Fields in the Po Valley, a Temperate Rice Area in Northern Italy," Int. J. Agron., vol. 2010, pp. 1–5, 2010, doi: 10.1155/2010/152158.
[86] Y. Zhang, "Effect of Biofertilizers on Rice Disease Resistance: A Comparison of Blast and Sheath Blight Resistance in China," J. Prog. Eng. Phys. Sci., vol. 4, no. 1, pp. 30–39, Feb. 2025, Accessed: Dec. 24, 2025. [Online]. Available: https://www.pioneerpublisher.com/jpeps/article/view/1210
[87] R. Rajput, A. Sharma, M. Rathod, and D. Katiyar, "Effect of Farmyard Manure and Biofertilizers on Productivity and profitability of Cucumber (Cucumis Sativus L.) cv. Pant Kheera-1," Int. J. Plant Soil Sci., vol. 35, no. 21, pp. 184–188, Oct. 2023, doi: 10.9734/ijpss/2023/v35i213961.
[88] J. L. Araujo et al., "Beneficial Microorganisms Affect Soil Microbiological Activity and Corn Yield under Deficit Irrigation," Agriculture, vol. 13, no. 6, p. 1169, June 2023, doi: 10.3390/agriculture13061169.
[89] A. Jalal, M. C. M. T. Filho, E. C. da Silva, C. E. da Silva Oliveira, L. A. Freitas, and V. do Nascimento, "Plant Growth-Promoting Bacteria and Nitrogen Fixing Bacteria: Sustainability of Non-legume Crops," in Nitrogen Fixing Bacteria: Sustainable Growth of Non-legumes, D. K. Maheshwari, R. Dobhal, and S. Dheeman, Eds., Singapore: Springer Nature, 2022, pp. 233–275. doi: 10.1007/978-981-19-4906-7_11.
[90] K. Alharbi, H. S. Osman, E. Rashwan, E. M. Hafez, and A. E.-D. Omara, "Stimulating the Growth, Anabolism, Antioxidants, and Yield of Rice Plants Grown under Salt Stress by Combined Application of Bacterial Inoculants and Nano-Silicon," Plants, vol. 11, no. 24, p. 3431, Jan. 2022, doi: 10.3390/plants11243431.
[91] A. Kushwaha and C. M. Mehta, "Pigeon Pea (Cajanus cajan L.) Based Intercropping System: A Review," Int. J. Plant Soil Sci., vol. 35, no. 18, pp. 1674–1689, Aug. 2023, doi: 10.9734/ijpss/2023/v35i183443.
[92] A. M. Prando, J. Z. Barbosa, A. B. D. Oliveira, M. A. Nogueira, E. J. Possamai, and M. Hungria, "Benefits of soybean co-inoculation with Bradyrhizobium spp. and Azospirillum brasilense: Large-scale validation with farmers in Brazil," Eur. J. Agron., vol. 155, p. 127112, Apr. 2024, doi: 10.1016/j.eja.2024.127112.
[93] B. N. Gnanesh et al., "Genetic mapping and quantitative trait locus analysis of resistance to sterility mosaic disease in pigeonpea [Cajanus cajan (L.) Millsp.]," Field Crops Res., vol. 123, no. 2, pp. 53–61, Aug. 2011, doi: 10.1016/j.fcr.2011.04.011.
[94] Sreethu S, V. Chhabra, G. Kaur, and B. Ali, "Biofertilizers as a Greener Alternative for Increasing Soil Fertility and Improving Food Security Under Climate Change Condition," Commun. Soil

Sci. Plant Anal., vol. 55, no. 2, pp. 261–285, Jan. 2024, doi: 10.1080/00103624.2023.2265945.

[95] Imran, "Integration of organic, inorganic and bio fertilizer, improve maize-wheat system productivity and soil nutrients," J. Plant Nutr., vol. 47, no. 15, pp. 2494–2510, Sept. 2024, doi: 10.1080/01904167.2024.2354190.

[96] X. Liang, S. Yu, Y. Ju, Y. Wang, and D. Yin, "Integrated Management Practices Foster Soil Health, Productivity, and Agroecosystem Resilience," Agronomy, vol. 15, no. 8, p. 1816, July 2025, doi: 10.3390/agronomy15081816.

[97] N. Akhtar et al., "Improvement of Plant Responses by Nanobiofertilizer: A Step towards Sustainable Agriculture," Nanomaterials, vol. 12, no. 6, p. 965, Jan. 2022, doi: 10.3390/nano12060965.

[98] S. Salimani, R. Verma, K. B. Kumar, and S. Mehta, "Impact of Biofertilizers and Integrated Nutrient Management on Transplanted Rice for Improving the Growth, Yield and Soil Quality: A Review," Int. J. Plant Soil Sci., vol. 37, no. 5, pp. 271–281, May 2025, doi: 10.9734/ijpss/2025/v37i55451.

[99] B. Dębska, J. Długosz, A. Piotrowska-Długosz, and M. Banach-Szott, "The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration—results from a field-scale study," J. Soils Sediments, vol. 16, no. 10, pp. 2335–2343, Oct. 2016, doi: 10.1007/s11368-016-1430-5.

[100] A. Jurado-Flores, L. G. Heredia-Martínez, G. Torres-Cortes, and E. Díaz-Santos, "Harnessing Microalgae and Cyanobacteria for Sustainable Agriculture: Mechanistic Insights and Applications as Biostimulants, Biofertilizers and Biocontrol Agents," Agriculture, vol. 15, no. 17, p. 1842, Aug. 2025, doi: 10.3390/agriculture15171842.

[101] S. Yadav et al., "Cyanobacteria-Pesticide Interactions and Their Implications for Sustainable Rice Agroecosystems," Int. J. Microbiol., vol. 2025, no. 1, p. 7265036, 2025, doi: 10.1155/ijm/7265036.

[102] M. H. Shahrajabian, Q. Cheng, and W. Sun, "Using Bacteria and Fungi as Plant Biostimulants for Sustainable Agricultural Production Systems," http://www.eurekaselect.com, Accessed: Dec. 24, 2025. [Online]. Available: https://www.eurekaselect.com/article/123485

[103] Z. Liu et al., "Native mixed microbe inoculants (M1H) optimize soil health to promote Cajanus cajan growth: the soil fungi are more sensitive than bacteria," Front. Microbiol., vol. 16, Mar. 2025, doi: 10.3389/fmicb.2025.1521064.

[104] X. Li et al., "Effects of Different Microbial Fertilizers on Growth and Rhizosphere Soil Properties of Corn in Newly Reclaimed Land," Plants, vol. 11, no. 15, p. 1978, Jan. 2022, doi: 10.3390/plants11151978.

[105] J. Gomis-Cebolla and C. Berry, "*Bacillus* thuringiensis as a biofertilizer in crops and their implications in the control of phytopathogens and insect pests," Pest Manag. Sci., vol. 79, no. 9, pp. 2992–3001, 2023, doi: 10.1002/ps.7560.

[106] M. Tariq, F. Jameel, U. Ijaz, M. Abdullah, and K. Rashid, "Biofertilizer microorganisms accompanying pathogenic attributes: a potential threat," Physiol. Mol. Biol. Plants, vol. 28, no. 1, pp. 77–90, Jan. 2022, doi: 10.1007/s12298-022-01138-y.

[107] N. Sharma, L. Mahawar, A. Mishra, and B. R. Albrectsen, "Microbial contributions to plant growth and stress tolerance: Mechanisms for sustainable plant production," Plant Stress, vol. 17, p. 100966, Sept. 2025, doi: 10.1016/j.stress.2025.100966.

[108] U. B. Ibrahim et al., "The Attributes of Biofertilizer as an Alternative to Chemical Fertilizer: A Mini Review," UMYU Sci., vol. 3, no. 1, pp. 208–214, 2025, doi: 10.56919/usci.2431.023.

[109] U. B. Kunwar, N. Manzoor, J. Wen, and N. R. Pandit, "Integrating Agronomic and Molecular Advancements to Enhance Nitrogen Use Efficiency (NUE) and Promote Sustainable Rice Production," Nitrogen, vol. 6, no. 2, p. 34, June 2025, doi: 10.3390/nitrogen6020034.

[110] P. M. Nkebiwe et al., "Effectiveness of bio-effectors on maize, wheat and tomato performance and phosphorus acquisition from greenhouse to field scales in Europe and Israel: a meta-analysis," Front. Plant Sci., vol. 15, Apr. 2024, doi: 10.3389/fpls.2024.1333249.

[111] P. Renganathan, L. A. Gaysina, and E. O. Rueda-Puente, "Microbial Biofertilizers for Salinity Stress Mitigation in Hydroponic Systems," Curr. Issues Mol. Biol., vol. 47, no. 12, p. 1029, Dec. 2025, doi: 10.3390/cimb47121029.

[112] M. B. Syiem and B. L. Kynshi, "Potential and Feasibility of Metal Cyanoremediation in the Environment," in Application of Microbial Technology in Wastewater Treatment and Bioenergy Recovery, S. Ray Chaudhuri, Ed., Singapore: Springer Nature, 2024, pp. 303–334. doi: 10.1007/978-981-97-3458-0_12.

[113] E. J. Tejada-Rodríguez, E. D. L. Cruz-Frías, and A. Arreguín, "Biofertilizers and Maize: Impacts on Growth and Productivity in Sustainable Agriculture," OALib, vol. 12, no. 10, pp. 1–16, 2025, doi: 10.4236/oalib.1114262.

[114] J. G. Osorio-Reyes et al., "Microalgae-Based Biotechnology as Alternative Biofertilizers for Soil Enhancement and Carbon Footprint Reduction: Advantages and Implications," Mar. Drugs, vol. 21, no. 2, p. 93, Feb. 2023, doi: 10.3390/md21020093.

[115] T. C. Sarker et al., "Soil Aggregation in Relation to Organic Amendment: a Synthesis," J. Soil Sci. Plant Nutr., vol. 22, no. 2, pp. 2481–2502, June 2022, doi: 10.1007/s42729-022-00822-y.

[116] U. De Corato, E. Viola, C. Keswani, and T. Minkina, "Impact of the sustainable agricultural practices for governing soil health from the perspective of a rising agri-based circular bioeconomy," Appl. Soil Ecol., vol. 194, p. 105199, Feb. 2024, doi: 10.1016/j.apsoil.2023.105199.

[117] M. M. A. Allouzi, S. M. A. Allouzi, Z. X. Keng, C. V. Supramaniam, A. Singh, and S. Chong, "Liquid biofertilizers as a sustainable solution for agriculture," Heliyon, vol. 8, no. 12, Dec. 2022, doi: 10.1016/j.heliyon.2022.e12609.

[118] A. M. Timofeeva, M. R. Galyamova, and S. E. Sedykh, "Plant Growth-Promoting Soil Bacteria: Nitrogen Fixation, Phosphate Solubilization, Siderophore Production, and Other Biological Activities," Plants, vol. 12, no. 24, p. 4074, Jan. 2023, doi: 10.3390/plants12244074.

[119] A. S. M. Elnahal et al., "The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review," Eur. J. Plant Pathol., vol. 162, no. 4, pp. 759–792, Apr. 2022, doi: 10.1007/s10658-021-02393-7.

[120] X. Song et al., "Microalgae-based biofertilizers improve fertility and microbial community structures in the soil of potted tomato," Front. Plant Sci., vol. 15, Dec. 2024, doi: 10.3389/fpls.2024.1461945.

[121] C. Feng, X. Zong, B. Cui, H. Guo, W. Zhang, and J. Zhu, "Application of Carrier Materials in Self-Healing Cement-Based Materials Based on Microbial-Induced Mineralization," Crystals, vol. 12, no. 6, p. 797, June 2022, doi: 10.3390/cryst12060797.

[122] J. Borgulat, K. Ponikiewska, Ł. Jałowiecki, A. Strugała-Wilczek, and G. Płaza, "Are Wetlands as an Integrated Bioremediation System Applicable for the Treatment of Wastewater from Underground Coal Gasification Processes?," Energies, vol. 15, no. 12, p. 4419, Jan. 2022, doi: 10.3390/en15124419.

[123] E. H. Yusuf, "WITHDRAWN: Fruit-infused dried carrots impact shelf life, nutrients, and health benefits," Food Chem. X, p. 102934, Aug. 2025, doi: 10.1016/j.fochx.2025.102934.

[124] A. Bianchi and F. Venturi, "Enhancing the Shelf Life of Food Products: Strategies, Challenges, and Innovations," Foods, vol. 14, no. 23, p. 4034, Jan. 2025, doi: 10.3390/foods14234034.

[125] B. K. A. Bellanthudawa et al., "A perspective on biodegradable and non-biodegradable nanoparticles in industrial sectors: applications, challenges, and future prospects," Nanotechnol. Environ. Eng., vol. 8, no. 4, pp. 975–1013, Dec. 2023, doi: 10.1007/s41204-023-00344-7.

[126] H. Zhang et al., "Recent advancements in encapsulation of chitosan-based enzymes and their applications in food industry," Crit. Rev. Food Sci. Nutr., vol. 63, no. 32, pp. 11044–11062, Dec. 2023, doi: 10.1080/10408398.2022.2086851.

[127] A. Khan et al., "Microbial bioformulation: a microbial assisted biostimulating fertilization technique for sustainable agriculture," Front. Plant Sci., vol. 14, Dec. 2023, doi: 10.3389/fpls.2023.1270039.

[128] T. P. Masere and S. H. Worth, "Factors influencing adoption, innovation of new technology and decision-making by small-scale resource constrained farmers: The perspective of farmers in lower Gweru, Zimbabwe," Afr. J. Food Agric. Nutr. Dev., vol. 22, no. 3, pp. 20013–20035, Sept. 2022, Accessed: Dec. 25, 2025. [Online]. Available: https://www.ajol.info/index.php/ajfand/article/view/231189

[129] N. U. Okorie, K. N. Kesit, and O. Uwemedimo, "enhancing agricultural productivity in akwa ibom state through human capacity strengthening for effective extension service delivery," J. Community Commun. Res., vol. 9, no. 1, pp. 129–137, June 2024, Accessed: Dec. 25, 2025. [Online]. Available: https://jccr.sccdr.org/index.php/jccr/article/view/193

[130] B. Pei et al., "Effects of Biofertilizer on Yield and Quality of Crops and Properties of Soil Under Field Conditions in China: A Meta-Analysis," Agriculture, vol. 15, no. 10, p. 1066, Jan. 2025, doi: 10.3390/agriculture15101066.

[131] J. Kaur, Baby, and Taman, "Constraints in Biofertilizer Industry and Future Scope," in Metabolomics, Proteomes and Gene Editing Approaches in Biofertilizer Industry, S. Kaur, V. Dwibedi, P. K. Sahu, and G. S. Kocher, Eds., Singapore: Springer Nature, 2023, pp. 1–19. doi: 10.1007/978-981-99-3561-1_1.

[132] P. Patel and A. Naik, "Ethical and Legal Issues in Microbial Products in India," in Agricultural Microbiology Based Entrepreneurship : Making Money from Microbes, N. Amaresan, D. Dharumadurai, and O. O. Babalola, Eds., Singapore: Springer Nature, 2023, pp. 81–100. doi: 10.1007/978-981-19-5747-5_5.

[133] S. K. Joshi and A. K. Gauraha, "Global biofertilizer market: Emerging trends and opportunities," in Trends of Applied Microbiology for Sustainable Economy, Elsevier, 2022, pp. 689–697. doi: 10.1016/B978-0-323-91595-3.00024-0.

[134] M. O'Callaghan, R. A. Ballard, and D. Wright, "Soil microbial inoculants for sustainable agriculture: Limitations and opportunities," Soil Use Manag., vol. 38, no. 3, pp. 1340–1369, 2022, doi: 10.1111/sum.12811.

[135] S. D. Peddle et al., "Practical applications of soil microbiota to improve ecosystem restoration: current knowledge and future directions," Biol. Rev., vol. 100, no. 1, pp. 1–18, 2025, doi: 10.1111/brv.13124.

[136] J. Li, J. Wang, H. Liu, C. A. Macdonald, and B. K. Singh, "Microbial inoculants with higher capacity to colonize soils improved wheat drought tolerance," Microb. Biotechnol., vol. 16, no. 11, pp. 2131–2144, Oct. 2023, doi: 10.1111/1751-7915.14350.

[137] B. Rojas-Sánchez et al., "Bioencapsulation of Microbial Inoculants: Mechanisms, Formulation Types and Application Techniques," Appl. Biosci., vol. 1, no. 2, pp. 198–220, Sept. 2022, doi: 10.3390/applbiosci1020013.

[138] J. Feng, J. Dou, and W. Wu, "Development of biochar-impregnated alginate beads for the delivery of biocontrol agents for peanut aflatoxin," Food Addit. Contam. Part A, vol. 39, no. 8, pp. 1487–1500, Aug. 2022, doi: 10.1080/19440049.2022.2085888.

[139] K. Rahimi Mamaghani, M. Alikarami, and H. Saremi, "Polymeric Hydrogels in Agriculture: Environmental Performance, Sustainability Challenges, and Future Perspectives," ACS Agric. Sci. Technol., vol. 5, no. 12, pp. 2341–2360, Dec. 2025, doi: 10.1021/acsagscitech.5c00808.

[140] Z. Qin, Y. Li, S. Deng, and X. Dou, "Big data-driven insights into soil-plant-microbe interactions: Mechanisms, applications, and sustainable management in paddy fields," Adv. Resour. Res., vol. 5, no. 2, pp. 772–792, 2025, doi: 10.50908/arr.5.2_772.

[141] F. Ewert, R. Baatz, and R. Finger, "Agroecology for a Sustainable Agriculture and Food System: From Local Solutions to Large-Scale Adoption," Annu. Rev. Resour. Econ., vol. 15, no. Volume 15, 2023, pp. 351–381, Oct. 2023, doi: 10.1146/annurev-resource-102422-090105.

[142] D. Wu, W. Wang, Y. Yao, H. Li, Q. Wang, and B. Niu, "Microbial interactions within beneficial consortia promote soil health," Sci. Total Environ., vol. 900, p. 165801, Nov. 2023, doi: 10.1016/j.scitotenv.2023.165801.

[143] M. Arıkan and T. Muth, "Integrated multi-omics analyses of microbial communities: a review of the current state and future directions," Mol. Omics, vol. 19, no. 8, pp. 607–623, 2023, doi: 10.1039/D3MO00089C.

[144] Y. Xing and X. Wang, "Precise application of water and fertilizer to crops: challenges and opportunities," Front. Plant Sci., vol. 15, Dec. 2024, doi: 10.3389/fpls.2024.1444560.

[145] B. Thakur and S. Kaur, "The Role of Artificial Intelligence in Biofertilizer Development," in Metabolomics, Proteomics and Gene Editing Approaches in Biofertilizer Industry: Volume II, S. Kaur, V. Dwibedi, and P. K. Sahu, Eds., Singapore: Springer Nature, 2024, pp. 157–176. doi: 10.1007/978-981-97-2910-4_9.

[146] G. E. Mushi, G. D. M. Serugendo, and P.-Y. Burgi, "Data management system for sustainable agriculture among smallholder farmers in Tanzania: research-in-progress," Inf. Technol. Dev., vol. 29, no. 4, pp. 558–581, Oct. 2023, doi: 10.1080/02681102.2023.2215528.

[147] L. E. Redmond, "Sustainability benefits of industrial symbiosis: Building value from stakeholders," IIIEE Master Thesis, 2023, Accessed: Dec. 25, 2025. [Online]. Available: http://lup.lub.lu.se/student-papers/record/9124504

[148] M. Oubohssaine, K. Rabeh, M. Hnini, and J. Aurag, "Microbial and biotechnological approaches to harness agricultural wastes for sustainable phosphorus management in crop production," Front. Agron., vol. 7, Dec. 2025, doi: 10.3389/fagro.2025.1686198.