



The Evolving Role of Bio-fertilizers in Climate-smart Agriculture- A Perspective on Sustainable Productivity, Adaptation and Mitigation: A Review

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ABSTRACT

The process of climate change poses unique threats to the global food security, necessitating some fundamental changes in agricultural production. Climate-smart agriculture (CSA) framework can be used to achieve sustainable productivity, better adaptation and less greenhouse gas emissions. Bio-fertilisers, preparations of useful microorganisms, which improve plant nutrient uptake and hardiness, have become indispensable in this regard. This review is a synthesis of the knowledge available on the use of bio-fertilizers to increase the use of nutrients, increase tolerance of plants to abiotic stress and decrease dependence on synthetic inputs to boost soil health and reduce environmental footprint. Bio-fertilizers work mechanically to enable fixation of nitrogen, solubilization of phosphorus, potassium and symbiotic acquisition of nutrients through the arbuscular mycorrhizal fungi. They also enhance the plant stress responses by accumulating osmolytes, regulating of phytohormones and antioxidants. All these advantages make bio-fertilizers indispensable when it comes to achieving the objectives of CSA. Nonetheless, its large scale use is hindered by the fluctuating efficacy of field and inadequate quality regulation, storage instability and lax regulations. Future studies are advised to focus on multi-omics to enhance strain development, development of efficient microbial consortia and improved encapsulation procedures in order to improve product stability. Field assessment should be done over a long term to authenticate the performance and supporting policies should be essential in scaling up. Combining these biological technologies and CSA concepts has significant prospects of producing robust and sustainable food systems.

Key words: Climate-smart agriculture, Food security, Greenhouse gases, Microbial inoculants, Soil health.

Global food security is increasingly strained by rapid population growth, escalating climate change impacts and finite natural resources (Simane *et al.*, 2025; Toromade *et al.*, 2024). Conventional agricultural practices, while historically boosting food production, are now under scrutiny for their significant environmental footprint. This includes intensive agrochemical use, soil degradation, biodiversity loss and substantial greenhouse gas (GHG) emissions such as nitrous oxide (N₂O) and methane (CH₄) (Aveni and Olagoke-Komolafe, 2024; Singh *et al.*, 2024). This unsustainable trajectory necessitates a shift toward more environmentally sound agricultural systems.

In response, the food and agriculture organization (FAO) developed climate-smart agriculture (CSA), a framework for adapting agricultural systems to ensure food security under climate change (FAO, 2025). CSA is built on three core, interconnected pillars: i) Sustainably increasing agricultural productivity and incomes; ii) Adapting and building resilience to climate change; iii) Reducing and/or removing GHG emissions where feasible (van Wijk *et al.*, 2020). Achieving these synergistic objectives demands innovative technologies that optimize resource use and enhance ecosystem resilience.

Within this holistic approach, bio-fertilizers emerge as a critical component. Bio-fertilizers are microbial preparations that, when applied to seeds, plants, or soil, colonize the rhizosphere or plant interior to enhance growth by improving nutrient availability (Nosheen *et al.*, 2021). Unlike synthetic

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fertilizers, which contribute to nutrient runoff, soil acidification and high GHG emissions, bio-fertilizers leverage natural microbial processes to improve nutrient cycling, soil health and plant stress tolerance.

This paper critically reviews the role of bio-fertilizers in advancing the objectives of CSA. We explore how these microbial inoculants contribute to sustainable productivity, climate adaptation and GHG mitigation. Furthermore, this review identifies key barriers to their widespread adoption and proposes future research directions required to realize their full potential within climate-smart agricultural systems.

Literature search strategy

The large scientific databases, including Web of Science, Scopus, PubMed, Google scholar and CAB abstracts were searched systematically. Both primary and secondary keywords on three thematic areas (search strategy) have been incorporated in the search strategy:

Bio-fertilisers: Biofertiliser, microbial inoculant, biological fertiliser, nitrogen fixing bacteria, phosphate solubilising bacteria, potassium mobilising bacteria, plant growth promoting rhizobacteria (PGPR) and mycorrhizal fungi.

Climate-smart agriculture: Climate-smart agriculture, CSA, sustainable agriculture, resilient agriculture, climate change adaptation, greenhouse gas mitigation, agricultural sustainability and soil health.

Agricultural results: Yield increase, crop productivity, nutrient use efficiency, drought tolerance, salinity tolerance, abiotic stress, nitrous oxide emission and methane emission.

Search queries were narrowed down with the help of Boolean operators (AND, OR, NOT). For example:

Biofertiliser or microbial inoculant and climate-smart agriculture or sustainable agriculture and crop productivity or nutrient use efficiency.

Reference lists of key review articles were also screened to identify any other relevant studies that were not discovered during the initial database search.

Study selection criteria

Inclusion and exclusion of the literature were founded on the following criteria:

Relevance: The most important priority was the studies, which directly determine the significance of bio-fertiliser in enhancing production, improving stability to climatic stress, or lowering GHG emissions in agriculture.

Publication type: Only the peer-reviewed articles and review papers, conference and technical reports of the recognised scientific organisations (e.g., FAO, IPCC) were taken into account.

Publication period: The search was wide but specifically those articles published between 2010 and 2025 were used to ensure that the current scientific innovations were included. Historical or conceptual background

Foundational papers which were written earlier were also reviewed.

Language: Only the publications that used English were taken into consideration.

Scope: The papers which are empirically evidence-based, contain modelling findings or theoretical models that would specifically address bio-fertilisers in relation to CSA principles were included. Poorly characterised articles whose isolations or characterisation of microbes, but not application in agriculture were never given consideration until they provided mechanistic insights into CSA functions.

Data extracting and synthesis

According to the selected publications, the most significant data were summarised and categorised according to the three pillars of CSA, sustainable productivity, adaptation and mitigation. The information to be captured was the following:

Mechanisms of action: The effectiveness of bio-fertiliser relies on biological processes which involve fixation of the nutrients, solubilisation, generation of phyto-hormones and biocontrol processes.

Effects on productivity: Quantitative or qualitative data of improvement in crop productivity, biomass growth or nutrient uptake efficiency.

Adaptation strategies: Experimental data have shown tolerance to abiotic stresses such as drought, salinity and extreme temperatures of plants.

Potential mitigation: The findings concerning the reduction of the GHG emissions (N_2O , CH_4) and the enhancement of the soil carbon sequestration contribution.

Challenges and limitations: The limitations on large-scale adoption include strain-specific performance, environmental heterogeneity, cost and regulatory limitations.

Future research directions: Identification of lapses in the current knowledge and recommendations of future studies.

The received information was synthesised and critically analysed in a systematic fashion to discover new trends, areas of consensus and deviant opinions all across the literature. This review is not a report of new experimental discoveries but a syntactic explanation of the current scientific knowledge which would inform future research, policy making and sustainable agriculture.

Climate-smart agriculture: A foundational framework

Climate-smart agriculture is an integrated approach, rather than a single practice, designed to address the challenges of food security and climate change simultaneously. Its framework rests on three interconnected pillars: sustainable productivity, enhanced adaptive capacity and greenhouse gas mitigation, which collectively provide synergistic benefits.

The first pillar, sustainable productivity, focuses on increasing agricultural yields and incomes through more efficient management of resources like water and nutrients, thereby minimising environmental impact. The second, adaptation, aims to strengthen the resilience of farming systems and communities against climate-related stressors such as extreme weather and pests. The final pillar, mitigation, seeks to reduce agriculture's carbon footprint by lowering emissions and increasing carbon sequestration in soil and biomass.

The interdependence of these pillars is a key strength of the CSA model. An intervention that supports one pillar often generates co-benefits for the others. For example, enhancing soil organic matter not only sequesters carbon (mitigation) but also improves soil water retention for drought resilience (adaptation) and increases nutrient availability for crops (productivity). Bio-fertilizers operate effectively at this intersection, representing a potent, integrated solution that aligns with the multifactorial goals of the CSA framework.

Bio-fertilizer: Diversity, mechanisms and benefits

Types and functions of bio-fertilizer

Nitrogen-fixing bacteria (NFB)

These are arguably the most familiar and well known positive microbes and they are both symbiotic and non-symbiotic/free-living. Symbiotic bacteria (*Rhizobacter*, *Bradyrhizobacter*, *Azorhizobacter*) exist on the roots of legumes, whereby they ensure that the ammonia (NH₃) produced by them is beneficial to the plant by fixing the nitrogen (N₂) in the atmosphere. According to what (Jaiswal and Dakora, 2025) has described, this process plays an important role in minimizing the need of synthetic nitrogen fertilizers. Conversely, free-living bacteria such as *Azotobacter*, *Azospirillum* and *Beijerinckia* fix nitrogen in the soil at the plant roots (the rhizosphere) or even at the plant tissue (endophytically). Crops that do not belong to the legumes enjoy this availability of nitrogen as has been pointed out by Asafar *et al.* (2021).

Phosphate solubilizing bacteria (PSB) and fungi (PSF)

The microbes such as *Pseudomonas*, *Bacillus*, *Penicillium* and *Aspergillus* help to dissolve the forms of phosphorus (P) found in the soil that are not utilized by plants such as rock phosphate (Sharma *et al.*, 2023). They convert them into forms that are available such as orthophosphate (Silva *et al.*, 2023). They achieve this through the release of organic acid (e.g. gluconic and citric acid) and phosphatase enzymes. The reported *Pseudomonas* include *P. cissicola*, *Pseudomonas striata*, *P. sturzeri*, *P. fluorescens*, *P. syringae*, *P. putida* and *P. putrefaciens* have been isolated from rhizosphere of chick pea, *Brassica*, soybean, maize and other crops. *B. brevis*, *B. subtilis*, *B. megaterium*, *B. pulvifaciens* and *B. polymyxa* from the rhizosphere of cereals, legumes, palm, chilli, oat, jute and arecanut (Gaur,

1999). *Jumpstart (R)* is the first P-solubilizing inoculants available in the market and the active ingredient is the fungus *Penicillium bilaiae* formerly known as *Penicillium bilaii*. *P. bilaiae* is known for its superior ability in Ca-P solubilization (Kucey, 1988). Among phosphate solubilizing fungi, *Aspergillus niger*, *A. nidulans*, *A. flavus*, *A. awamori*, *A. fumigatus*, *A. carbonum*, *A. terreus* and *A. wentii* have been reported from the rhizosphere of soybean, maize, chilli, acidic lateritic soil, tista soils and compost (Prerna and Kapoor, 1997).

Potassium solubilizing bacteria (KSB)

Other species such as *Bacillus mucilaginosus* help to incorporate potassium in plants by releasing insoluble minerals (e.g., feldspar) into soluble forms (through acidolysis and chelation) (Olaniyan *et al.*, 2022).

Arbuscular mycorrhizal fungi (AMF)

Being obligate symbionts of most soil plants, AMF spread a massive hyphal network well beyond the root depletion zone that has a strong positive impact on the uptake of immobile nutrients such as phosphorus and zinc and enhancing water uptake (Holly *et al.*, 2025).

Plant growth-promoting rhizobacteria (PGPR)

This heterogeneous population of bacteria (*Pseudomonas*, *Bacillus*, *etc.*) enhances the vitality of plants by a number of different mechanisms, including the synthesis of phytohormones (Sun *et al.*, 2024), anti-pathogenic biocontrol effects (Al Raish *et al.*, 2025) and response to stress in plants (Alonazi *et al.*, 2025).

Advantages of bio-fertilizer over synthetic fertilizers

Environmental protection: They lower the chemical run-off, decrease the pollution of soil and water and reduce the emission of greenhouse gases associated with the production and application of fertilizer.

Enhanced soil health: Bio-fertilizer can improve the structure and increase the organic levels of the soil and the microbial complexity that contributes to the restoration of ecological health of degraded soil (Wei *et al.*, 2024).

Long-term economic saving: They might save important economic benefits to farmers by slowing down the use of costly synthetic fertilisers in the long term (Diksha *et al.*, 2022).

Improved nutrient efficiency: They also help to increase the natural cycling/availability of nutrients, so that plants can absorb more and emit less.

The nexus: Bio-fertilizer as pillars of climate-smart agriculture

Enhancing sustainable productivity

Bio-fertilizer plays an important role in all three pillars of CSA, which serve as a biologically motivated route to more robust and sustainable agricultural systems.

Improved nutrient use efficiency (NUE)

The primary function of bio-fertilizers is to improve the availability and plant assimilation of essential nutrients (Kumar *et al.*, 2024; Mtaita *et al.*, 2019). Nitrogen-fixing bacteria lessen the dependence on synthetic nitrogen, a product that is energy-intensive to manufacture and a significant source of N₂O emissions. Concurrently, phosphate- and potassium-solubilizing bacteria convert insoluble soil nutrients into plant-available forms, thereby optimising the use of natural reserves and augmenting the effectiveness of applied fertilizers (Nath *et al.*, 2017). Furthermore, arbuscular mycorrhizal fungi (AMF) act as an extension of the root system, significantly boosting the absorption of nutrients such as phosphorus, particularly in deficient soils (Liang *et al.*, 2022). By enhancing overall nutrient use efficiency (NUE), bio-fertilizers can substantially decrease nutrient runoff into waterways, thus mitigating eutrophication and reduce the required frequency of fertilizer applications.

Increased crop yield and quality

Much field research has indicated that the application of bio-fertilizer leads to a significant increase in the yield of several crops such as cereals, legumes and vegetables (Mutetwa *et al.*, 2023; Guda *et al.*, 2020; Mutetwa *et al.*, 2019). Besides increasing the quantity, bio-fertilizer also enhance the nutritional quality of the produce by aiding the plants to absorb more micronutrients and generate nutritionally useful compounds like vitamins and antioxidants (Dasgan *et al.*, 2023).

Stress tolerance and resilience

As a result of climate change, which results in increased and more severe abiotic stresses like drought, salinity, heat and heavy metal toxicity, bio-fertilizer has never been more important than it is today.

Drought and water stress tolerance

Water scarcity is a primary constraint on global crop yields. Beneficial soil microbes, including plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), enhance plant drought tolerance through several mechanisms. They improve water acquisition; AMF hyphae explore soil beyond the rhizosphere (Torres *et al.*, 2024), while PGPR promote more extensive root systems to access greater soil volumes (Buqori *et al.*, 2025; Bouremani *et al.*, 2023). These microbes also aid osmotic adjustment by facilitating the synthesis of compatible solutes like proline and sugars, which maintain cellular turgor (Ghosh *et al.*, 2021). Additionally, certain PGPR produce ACC deaminase to lower detrimental, stress-induced ethylene levels (Alonazi *et al.*, 2025; Timifeeva *et al.*, 2024). Finally, they strengthen the plant's antioxidant defenses, mitigating oxidative damage from reactive oxygen species (ROS) that accumulate under water deficit conditions (Hasanuzzaman *et al.*, 2021).

Salinity tolerance

Soil salinity adversely affects vast agricultural lands, an issue exacerbated by shifting precipitation patterns and rising sea levels. Bio-fertilizers can enhance plant tolerance to this salt-induced stress (Agnihotri and Ashwini, 2024). For instance, salt-tolerant PGPR can limit sodium (Na⁺) accumulation in shoots by inhibiting its uptake or sequestering it within root vacuoles (Ilangumaran and Smith, 2017). As salinity often impedes nutrient absorption, these microbes also improve the uptake of essential minerals (K⁺, Ca²⁺, Mg²⁺) and help maintain a favorable K⁺/Na⁺ ratio, which is critical for survival (Zafar *et al.*, 2021). Similar to their role in drought response, these bio-fertilizers also stimulate the production of osmolytes and antioxidant enzymes to protect against cellular damage in saline environments (Zaki *et al.*, 2025).

Heat and other abiotic stresses

Elevated temperatures trigger heat stress, resulting in substantial dehydration and diminished photosynthetic capacity in plants (Liu *et al.*, 2020). Plants inherently mitigate these impacts by modifying respiration, transpiration and internal solute levels to regulate cooling and cell turgor (Wang *et al.*, 2020). Bio-fertilizers can bolster these inherent defences. While their contribution to heat tolerance is less explored than in drought scenarios, bio-fertilizers demonstrate considerable promise by facilitating nutrient uptake, water regulation and other physiological adaptations (Chaudhary *et al.*, 2022). Moreover, they improve soil quality, enhancing overall ecosystem robustness. By fostering plant vitality and nutrient status, bio-fertilizers boost plant vigour and resilience against multiple, often simultaneous, stressors (Diagne *et al.*, 2020).

Strengthening adaptive capacity**Improving soil health and water management**

Bio-fertilizer promote healthy soil. The microbial activity enhances the soil structure that enhances aeration and uptake of water. This improves the soil as it minimizes soil erosion, better water retention to prevent drought and improves drainage during heavy rainfall. Moreover, the greater the amount of microbial life, the more soil organic matter, which is the basis of any good, healthy soil.

Conserving biodiversity

Bio-fertilizer reduce the use of synthetic fertilizers and pesticides, thus supporting a rich population of soil microorganisms. This subterranean ecosystem plays a critical role in terms of distributing nutrients, curbing diseases and maintaining stability in general. The natural selection of a wide range of soil microbiome is more resilient to traditional environmental stressors such as temperature and water changes.

Strengthening root systems

Most bio-fertilizers contain natural hormones which promote longer and greater root growth. An established

root system helps plants to absorb water and nutrients in a bigger amount of soil, which makes them much more flexible to the available resource changes.

Contributing to climate change mitigation

Mitigation of nitrous oxide (N₂O) emissions

Synthetic nitrogen fertilizers dominate as the largest anthropogenic source of N₂O, a potent greenhouse gas with a global warming potential 265 times greater than CO₂ (Pan *et al.*, 2022; IPCC, 2014). Bio-fertilizers offer a key solution by reducing dependence on synthetic inputs. They enhance natural processes like biological nitrogen fixation (BNF) and improve crop nitrogen use efficiency (NUE), thereby lowering both chemical fertilizer use and associated N₂O emissions from production and application (Samantaray *et al.*, 2024; Santillano-Cázares *et al.*, 2022). Studies confirm that partial or full replacement of synthetic fertilizers with bio-fertilizers can significantly curb N₂O emissions from soil nitrification and denitrification (Huang *et al.*, 2025). Emerging evidence suggests certain bio-fertilizer strains may also modify soil microbial communities to favour nitrogen-cycling pathways with reduced N₂O output, though further ecosystem-scale research is needed (Waqas *et al.*, 2025; Li *et al.*, 2023).

Reduction of methane (CH₄) emissions

Livestock enteric fermentation and flooded rice paddies are major CH₄ sources. While bio-fertilizers minimally affect livestock-related CH₄, they can influence rice agro-ecosystems. For instance, bio-fertilizers that stimulate robust root growth may enhance rhizosphere oxygenation, altering microbial activity by suppressing methanogenic archaea or promoting methanotrophs, depending on soil conditions (Thao *et al.*, 2024; Malyan *et al.*, 2021; Serrano-Silva *et al.*, 2014). Additionally, improved nitrogen supply via BNF fosters vigorous rice growth, potentially modifying soil redox dynamics and organic matter decomposition, though the net effect on methanogenesis remains complex and warrants deeper investigation.

Soil carbon sequestration enhancement

Bio-fertilizers bolster carbon sequestration through multiple mechanisms. They promote plant growth, increasing root exudates and microbial activity that stabilize soil organic carbon (SOC) (Wei *et al.*, 2024; Yang *et al.*, 2023; Tian *et al.*, 2022). Beneficial microorganisms, such as arbuscular mycorrhizal fungi (AMF), produce glomalin, a glycoprotein that enhances soil aggregation, protecting organic matter from degradation (Son *et al.*, 2024; Staunton *et al.*, 2020). Furthermore, bio-fertilizers may enable reduced-tillage systems by improving nutrient availability and plant resilience, mitigating CO₂ emissions from soil disturbance (Mühlbachová *et al.*, 2023). Collectively, these processes enhance soil carbon storage, fostering agricultural systems capable of offsetting atmospheric CO₂.

Reduced energy consumption

The production of synthetic fertilizers, especially those based on nitrogen through the Haber-Bosch process, consumes huge amounts of energy from fossil fuels. The use of bio-fertilizer will result in reduced demand of these products, directly resulting in a reduced energy footprint in the agricultural sector and reduces the embedded CO₂ emissions in the industrial sector (Mahmud *et al.*, 2021).

Challenges and limitations in bio-fertilizer adoption

Inconsistent performance

The unpredictable behavior of bio-fertilizer under diverse field conditions, soil type, pH levels, organic matter, temperature, moisture levels and presence of microbial community is a major challenge (Baloch, 2025). As an example, a strain of microbes that has been effective in one farm may not be effective in another. These kinds of unreliable outcomes can reduce confidence among farmers, hence reducing the adoption rate.

Quality assurance and standardization

Commercial sale of bio-fertilizers has a high degree of inconsistency in terms of their viable cells count, levels of purity and longevity (Ivette *et al.*, 2025). Lack of strict quality assurance measures and standard procedure in the production, distribution and consumption of products is often the reason why we end up with items which fail to perform as they are being marketed (Matura *et al.*, 2023).

Product stability and storage

Most microbial inoculants are prone to environmental factors, including heat, moisture and ultraviolet light that may severely reduce their survival and performance (Rojas-Sánchez *et al.*, 2022). This sensitivity poses great logistical challenges to their transportation, storage and consumption especially in remote or poorly equipped areas.

Farmer knowledge and acceptance

The lack of adequate information about the benefits, proper methods of application and long-term effects of bio-fertilizer is some of the factors most farmers, particularly those in the developing countries, lack. More so, initial investment, the perception that they do not work as fast as using chemical fertilizers and general aversion to taking risks, among others, can deter farmers using them (Hasan *et al.*, 2025).

Regulatory oversight

Inadequate or inconsistent laws on the authorization, production and distribution of bio-fertilizer in most countries are detriments to global commerce and hindrances to innovations (Masso *et al.*, 2013). Clear guidelines are required to ensure that products are safe, effective, as well as being environmentally harmless.

Interaction with agricultural chemicals

The widespread use of pesticides, fungicides as well as herbicides in the traditional farming systems can damage

the life and functioning of the useful microbial inoculants. The most important thing is to either develop microbial strains that could resist such widespread agricultural chemicals or promote the adoption of integrated pest management strategies with the use of bio-fertilizer (Raimi *et al.*, 2021).

Opportunities

Better formulations: Encapsulation, nano-formulations and other carrier materials may lead to the improvement of the shelf-life, viability and transport of bio-fertilisers and make them easier and more efficient in a diverse spectrum of conditions.

Integrated nutrient management (INM): The bio-fertilisers are most effective when used together with other nutrient management initiatives like reduction of the use of synthetic fertilisers and organic amendments. One of the avenues of synergizing dividends is through marketing INM solutions.

Policy support and subsidies: Governments can also be quite significant by providing policy endorsement, subsidies and other financial incentives, as well as the creation of clear policy guidelines that would promote production and utilization of bio-fertilisers.

Extension services and farmer education: Extension Services and field demonstrations are significant in terms of educating the farmer on the advantages, correct usage and control of bio-fertilisers.

Biotechnology and precision agriculture: Precision farming techniques of applying bio-fertilisers can be optimised to ensure that the correct microbes are used at the correct site at the correct time and therefore the highest efficacy is attained with minimum costs.

Research and development: It is worthwhile to note that the research ought to proceed in exploring the complex interactions between the microbes, plants and soil in different environmental conditions in an attempt to realise the full potential of bio-fertilisers.

Future directions and research gaps

Improving strains with advanced 'Omics' techniques

Modern 'omics' fields, including genomics, transcriptomics, proteomics and metabolomics, provide powerful tools to identify superior microbial strains. These techniques help decipher complex plant-soil-microbe interactions and elucidate the molecular basis of plant growth-promoting (PGP) traits and stress resilience (Yu *et al.*, 2025; Jain *et al.*, 2024). This understanding facilitates the rational design and, where regulations permit, the genetic engineering of more robust and effective inoculants tailored to specific agricultural environments.

Creating consortia of multiple strains

While single-strain microbial inoculants have demonstrated efficacy, the complex soil ecosystem and plant requirements

frequently necessitate microbial consortia. These mixtures leverage complementary functionalities, such as nitrogen-fixing bacteria combined with phosphate-solubilizing and other plant growth-promoting rhizobacteria. Further investigation is warranted to discern synergistic microbial partnerships, elucidate ecological interactions like competition and quorum sensing and refine formulation strategies for enhanced and consistent performance (Jiang *et al.*, 2025).

Advanced encapsulation and formulation methods

There is a need to come up with new formulation techniques, including micro-encapsulation, nano-formulations and granule based products, which enhance microbial viability, shelf life, stress tolerance and controlled release into the rhizosphere (Brondi *et al.*, 2025). In such a way, they can significantly increase the credibility of their use and become accessible to farmers.

Long-term field studies and agro-ecological mapping

To ascertain the long-term viability of bio-fertilizers across diverse agro-ecological settings, extended field trials are crucial. Such research, conducted in varied locations and under differing climatic and farming conditions, will generate essential data for farmer guidance and policy development. Furthermore, precision agriculture tools can facilitate precise matching of bio-fertilizer types to specific soil and crop requirements.

Evaluating ecological and economic impacts

A comprehensive economic analysis is needed to establish the long-term profitability of bio-fertilizers for farmers, accounting for reduced input costs, stable yields and enhanced ecosystem services. Furthermore, a lifecycle analysis (LCA) is required to quantify environmental benefits, particularly reduced greenhouse gas emissions, from production to field application.

Enhancing policy support and farmer outreach

Supportive policies and clear regulations are needed to govern bio-fertilizer production, quality assurance and promotion. Furthermore, robust extension services must educate farmers on optimal application methods to facilitate the adoption of modern farming systems.

Combining with other CSA methods

Future research should explore the synergy between bio-fertilizers and other CSA strategies, such as conservation agriculture, improved organic matter management and integrated nutrient plans, to enhance agricultural productivity, climate adaptation and environmental mitigation.

CONCLUSION

Bio-fertilizers are a fundamental technology for implementing CSA. By enhancing nutrient use efficiency, increasing plant resilience to abiotic stress and reducing greenhouse gas emissions, they directly address the triple-

win objectives of CSA. Leveraging microbial symbiosis and metabolic diversity, bio-fertilizers provide a biologically intensive, environmentally benign and economically viable alternative to synthetic chemical inputs. However, realising their transformative potential requires a concerted, interdisciplinary research agenda. To overcome challenges such as inconsistent performance, quality control and farmer acceptance, scientific innovation, robust validation and supportive policy frameworks are necessary. The future of global food security under climate change depends on our ability to integrate these sustainable biotechnologies into mainstream agriculture. The widespread adoption of bio-fertilizers is therefore critical to developing climate-intelligent agri-food systems that are productive, resilient and environmentally sustainable.

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Disclaimers

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Informed consent

This is a review article based on published literature and does not involve any human or animal participants, therefore informed consent is not applicable.

Conflict of interest

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