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REVIEW

Bioinoculants in climate-smart agriculture: Adaptation strategies for stress mitigation and crop productivity

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Abstract

Background: Climate change poses significant threats to global agriculture, intensifying the effects of biotic and abiotic stresses that reduce crop production and imperil food security. Bioinoculants, specifically arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR), and other beneficial microbial consortia, offer potential, eco-friendly alternatives to traditional agrochemical fertilizers within the structure of climate-smart agriculture. Methods: This review explores the mechanisms through which bioinoculants promote plant adaptation and mitigate stress, including their roles in nutrient acquisition, antioxidant synthesis, modulation of phytohormones, and improvement of soil structure and health. Results: Diverse applications of bioinoculants are discussed, with emphasis on enhancing crop yield and resilience under various harsh climate conditions, including salinity, drought, and extreme temperatures. The review critically peruses the challenges and limitations of bioinoculant use, such as their interaction with the native soil microbial community, variable efficacy, formulation stability, and scalability. Conclusions: By synthesizing current advances and identifying knowledge gaps, this review provides a comprehensive evaluation of the potential and limitations of bioinoculants in advancing climate-smart agriculture and offers strategic insights for researchers, policy makers, and practitioners dedicated to the development of agricultural sustainability.

Keywords: abiotic stress, arbuscular mycorrhizal fungi, extreme weather, food security, regenerative agriculture, plant growth-promoting rhizobacteria

Background

A recent survey of the global risks report between 2021 and 2022 revealed that the two most significant dangers the world will face in the next decade are extreme weather and climate action failure (McLennan, 2022). These climate-associated dangers are intensified by rapid human population growth, with the global population having exceeded 8.2 billion in 2024 (Lam, 2025) and is expected to reach 9.5 billion by 2050 (Lautensach and Lautensach, 2020). The merging of extreme weather events and population pressure makes food security an urgent concern facing the 21st century. To address this challenge, agricultural production of both food and non-food produce must increase by at least 60% by 2050 compared to 2005 levels (McKenzie and Williams, 2015).

To address the interlinked challenges of agriculture and climate change, the FAO introduced the concept of climate-smart agriculture (CSA) in 2010. CSA is a model designed to improve agricultural productivity, enhance climate resilience, and reduce greenhouse gas emissions (Saj *et al*., 2017). This approach provides a pathway to address hunger, poverty, and environmental degradation through improving food security, fostering resilience to climate impacts, and promoting sustainable resource management (Cernev and Fenner, 2020; McLennan, 2022). Incorporating CSA

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systems into policies, investments, and agricultural practices will greatly enhance climate change resilience in agricultural systems while safeguarding the well-being of present and future generations (Matteoli *et al*., 2020).

The concept of CSA integrates three key components, including economy, society, and environment, which must work together to address climate change-related threats to food security and sustainable agricultural development (Matteoli *et al*., 2020). The specific objectives of CSA are reflected in what is known as a 'triple-win' outcome, which incorporates adaptation, mitigation, and food security. This triple-win approach aims to improve food security and livelihoods through sustainably increasing agricultural productivity and income. This is achieved through improved crop varieties, efficient water management, and sustainable land management practices. Moreover, CSA enhances the ability of agricultural systems to adapt and build resilience to climate change impacts. These impacts include unpredictable rainfall patterns, droughts, and pest/disease outbreaks. The major strategies for building resilience involve diversifying crops, using stress-tolerant varieties, managing risks, and improving ecosystem services (Saj *et al*., 2017).

Over the past 10 years, CSA has seen rapid breakthroughs and progress in enhancing conservation agriculture (Ngoma *et al*., 2021), crop breeding (Zhao *et al*., 2023), crop variation planting (Descheemaeker *et al*., 2020), integrated management practices of soil fertility (Bayu, 2020), and weather index-based insurance (Kramer *et al*., 2019). A notable area of development in sustainable agriculture has been the use of biological soil amendments, which encompass three main categories, such as biofertilizers, bioinoculants, and biostimulants (Schütz *et al*., 2018). Table 1 highlights the comparison among bioinoculants, biofertilizers, and biostimulants. However, the success of these biological amendments varies based on factors such as soil type and crop variety. Therefore, continued investigations to validate their contributions and support toward CSA objectives and food security remain critical.

In particular, the use of bioinoculants, such as living bacterial, fungal, algal, and consortia inoculants, represents the main growth drivers for organic farming and climate-adapted agriculture. These biological amendments enhance plant nutrient availability and acquisition, increase stress tolerance in plants, improve plant water use efficiency, and advance integration with precision agriculture (Thomas and Singh, 2019). Bioinoculants are considered significant components of CSA and among the most successful strategies for climate change-adapted sustainable agriculture (Tan *et al*., 2022). Recent trends in bioinoculant application include increased research and development in microbial consortia formulations, enhanced technologies for field efficiency, and the development of region-specific microbial strains. They represent a viable solution to address major environmental sustainability challenges regarding chemical fertilizers while meeting the growing need for global food security (Mohanty and Swain, 2018). The bioinoculants' mechanism of action depends on their ability to interact with plants and soil, influence soil microbial communities, and modulate plant physiology and metabolism. These mechanisms result in diverse impacts, including improved soil structure and water retention, suppressed phytopathogens and diseases, enhanced biological nitrogen fixation, production of plant growth-promoting compounds, phosphorus solubilization, and mobilization of other essential nutrients (Suman *et al*., 2022). Climate change threatens food security through crop damage, reduced yields, harvest failures, and increased pests and diseases, necessitating sustainable approaches such as CSA (Tan *et al*., 2022). Despite promising greenhouse results, field-level validation of bioinoculants under diverse climatic conditions remains limited (Tan *et al*., 2022). This review, therefore, critically discusses the role of bioinoculants in CSA, highlighting their mechanisms, applications, limitations, and future potential in ensuring food security under climate stress.

Present climate change-related agriculture challenges

IMPACTS OF CLIMATE CHANGE ON AGRICULTURE

The agriculture industry globally faces immense climate change-related challenges, including water shortages and increased temperatures (Shahzad *et al*., 2021). Rising global seasonal temperatures may result in intense and frequent heat waves, which may negatively affect crop productivity, impair crop growth, and reduce crop yields. In regions where temperatures are near the physiological maxima for crops, increased temperature will impact crop productivity instantaneously within the same growing season (Tangney, 2020). The impact of global warming on soils and plants is expressed in alterations to their physiological, morphological, and biochemical processes (Fig. 1).

Yadav *et al*. (2021) estimate that global crop production could decline by 3–16% by 2080 and up to 40% by 2100, with severe implications for developing regions, particularly reliant on rain-fed agriculture. Temperature is a critical determinant of crop performance; therefore, different crop cultivars respond differently to various degrees of temperature at the plant stage of development and reproduction throughout their life cycle. For instance, a 1–2°C rise in average global temperature accompanied by an increased frequency of heat waves induces shorter, faster, and earlier growing seasons in some crops (Brás *et al*., 2021), including significant increases in heat stress risk and evapotranspiration in crops (Hassan *et al*., 2021).

Further, climate variability causes smallholder farming to suffer, leading to decreased crop production, food shortfall, and income (Sibanda *et al*., 2017). Data from Ethiopia showed that extreme climate events and variations intensely impacted subsistence food production and caused about 66.9% of sample households to experience food insecurity (Ayal *et al*., 2023). The frequency and intensity of extreme climate events such as hurricanes, hot days and nights, protracted growing season spans, and elevated CO_2 concentrations directly impact agriculture, causing substantial crop losses, damaging agricultural infrastructure, and interrupting food supply chains (Sibanda *et al*., 2017). In addition, the direct consequences of climate change on agricultural production are predicted to alter plant growth and yield over time globally, particularly in developing nations where food crop production is the principal source of income (Brás *et al*., 2021).

This calls for us not only to improve agricultural productivity and ensure food sufficiency but also to reduce the adverse effects of climate change and agricultural greenhouse gas emissions. Several technologies, like carbon fixation technology, can increase GHG absorption, while renewable energy and alternative energy technologies can regulate GHG emissions, specifically elevated CO_2 levels. Also, acclimatize to climate change by growing new crop varieties and changing agricultural production structures. These technologies can contribute substantially to reducing agricultural GHG emissions, particularly CO_2 and their impacts (Tetteh *et al*., 2021). In addition, information systems in CSA provide crucial data support for agricultural management and development, though challenges remain in standardization and data security (Raj and Raman, 2017). However, addressing the core climate stressors requires more direct interventions.

While climate change presents numerous challenges, including increased temperature, extreme wet weather events, GHG emissions, and changes in ecosystem dynamics, one of the most persistent problems is reduced global rainfall patterns (drought),

Table 1. Comparison among bioinoculants, biofertilizers, and biostimulants.

Feature	Bioinoculants	Biofertilizers	Biostimulants	Reference
Definition and composition	A term often used interchangeably with biofertilizers, consist of beneficial soil microorganisms' strains that become active when inoculated into the soil. Live beneficial microorganisms, when applied to soil, seeds, or plant tissues, colonize the plant internal tissues or rhizosphere. They increase nutrient accessibility or uptake, enhance soil health, promote plant growth, and advance stress resilience.	Inexpensive natural products containing one or more live microbial species that supplement chemical fertilizers. Formulation of containing live or latent microbial strains that specifically increase the availability and uptake of major nutrients to plants	Microorganisms or non-microbial substances that stimulate natural processes to augment nutrient uptake, crop quality, and stress tolerance, when applied in small amounts can improve plant growth, health, seed quality, stimulate root development when applied on seeds, soil, or plants, and crop yield	Sahu and Brahmaprakash (2016); Igiehon and Babalola (2017); Rouphael and Colla (2020); Hamid *et al.* (2021); Maitra *et al.* (2021)
Common examples	PGPR (*Azospirillum*, *Rhizobium);* AMF (*Glomus* spp.), and *Trichoderma*	AMF, Cyanobacteria, Azotobacter, Phosphobacteria, and Cyanobacteria	Seaweed extracts, humic or fulvic acids, amino acids, protein hydrolysates, chitosan, beneficial fungi or algae extracts	Sahu and Brahmaprakash (2016); Maitra *et al.* (2021); Tarafdar (2022)
Mode of action	Enhance the uptake of essential nutrients, N, P, and K, solubilize P and K, atmospheric N fixation, enhance the production of phytohormones, directly suppress pathogens, induce systemic resistance (IRS), and improve soil aggregation	Atmospheric N fixation, solubilize potassium, phosphorus, and zinc solubilization, induce the production of plant growth regulators to directly provide nutrients or nutrient bioavailability	Stimulate plant metabolic processes, improve nutrient use efficacy, enhance soil fertility and promote hormones stimulation and elicitors. Examples are non-microbial formulations, like seaweed extracts, humic acids, fulvic acids, and amino acids	Thomas and Singh (2019); Chaudhary *et al.* (2022); Jmaili *et al.* (2025)
Stress mitigation	Effective against both biotic (disease) and abiotic (drought, salinity, and extreme heat) stress through induced systemic resistance (IRS) and enhanced soil health	Indirectly mitigate stress by improving plant nutrition and bolstering plant health against stresses	Primarily focus on improving abiotic stress (drought, salinity, and high temperature) tolerance through the regulation plant metabolism and stress responses	Chaudhary *et al.* (2022); Franzoni *et al.* (2022); Kumar *et al.* (2022)
Role in climate-smart agriculture	Reduces artificial inputs, improve nutrient cycling, promote carbon sequestration, and promote soil microbial diversity and aggregation	Reduces the need for chemical fertilizers. Improves soil fertility and supports sustainable nutrient cycling	Promote plant growth and yield under stress. Enhances nutrient and water use efficiency	Mohanty and Swain (2018); De Vasconcelos and Chaves (2019); Thomas and Singh (2019)
Mode of application	Unique application, include seed coating, foliar or soil drenching, and root dipping may colonize plant tissues	Often applied through root dipping, and soil or seed inoculation	Broadly applied as a suspension or solution, such as seed treatment, soil application, foliar spray, and fertigation	Calvo *et al.* (2014); Jambhulkar *et al.* (2016); Kalidas-Singh and Thakuria (2018)
Long-term soil Effects	Advances soil structure, aggregation, and microbiome diversity	Improves nutrient cycling and soil fertility	Enhances soil organic matter, improves and water retention and soil particularly organic substance	Kalidas-Singh and Thakuria (2018); Rouphael and Colla (2020); Suman *et al.* (2022)
Regulatory status	Regulated as Plant Growth-Promoting Microorganisms (PGPM) or microbial plant aids	Regulated specifically as biofertilizer products	More regulated when used as living components or often less strict for non-living substances	dos Reis *et al.* (2024); Santos *et al.* (2024); Sible *et al.* (2025)

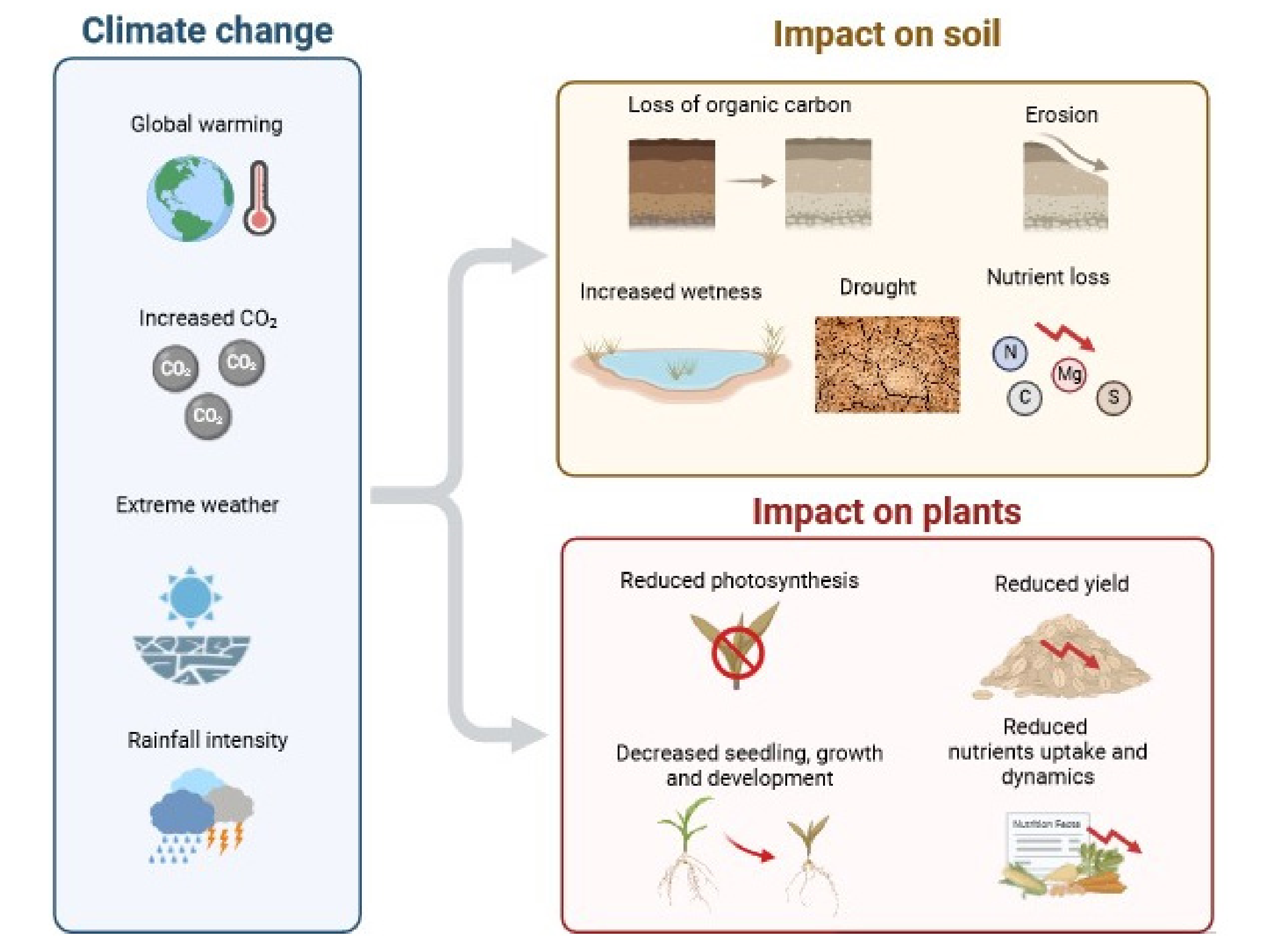

Fig. 1. Impact of global warming on soil properties and plant responses. This figure was created and modified using BioRender (Available at: https://biorender.com/, accessed 29 October 2024), an online tool. Legend: CO_2: Carbon dioxide; N: Nitrogen; C: Carbon; Mg: Magnesium; S: Sulfur.

which can have distressing effects on agriculture and food security. This is where biotechnological solutions like bioinoculants become particularly valuable, as they can enhance plant resilience to drought stress and other climate-related challenges while simultaneously improving soil health and nutrient availability. Auspiciously, recent developments in biotechnology propose that bioinoculants may proffer a promising solution and strategies to mitigate the impact of drought.

BIOINOCULANTS: AN INNOVATIVE APPROACH FOR CLIMATE-SMART AGRICULTURE

Bioinoculants as live microbial formulations present a novel approach to sustainable agricultural practices, significantly compared to the use of chemical fertilizers. Accordingly, studies have proved the advantages and novelty of bioinoculants over the application of traditional chemical fertilizers (Orozco-Mosqueda *et al*., 2021). Bioinoculants support plant adaptation to drought, flooding, and extreme temperatures. They enhance nutrient uptake and improve resilience without contributing to soil degradation (Nwachukwu *et al*., 2024). Furthermore, these bioinoculants are biodegradable, making them ecologically friendly alternatives to chemical fertilizers; hence they do not aid soil degradation and environmental pollution, which are general problems connected with the excessive application of chemical fertilizers (Rahman and Zhang, 2018).

Unlike broad-spectrum chemical fertilizers, bioinoculants target specific plant growth-promoting traits, such as nitrogen fixation, phosphate solubilization, and phytohormone synthesis, ensuring efficient resource use and reducing nutrient imbalances (Naamala and Smith, 2020; Orozco-Mosqueda *et al*., 2021; Shah *et al*., 2021). Their mechanisms directly improve plant health, enhance resilience to climate stress, and preserve soil quality, which distinguish them as significant tools for CSA.

Mechanisms of action of bioinoculants

Enhanced nutrient cycling and uptake

Extreme climate conditions frequently can lead to soil nutrient shortages or imbalances, which can place plants under stress. Bioinoculants can improve nutrient uptake and availability, aiding plants in maintaining their nutrient levels and growth even under unfavourable conditions (Khan *et al*., 2021). The functions and traits of bioinoculants are associated with the mitigation of water use efficiency, improved nutrient availability, and the effective uptake of essential nutrients such as nitrogen, potassium, and phosphorus by plants. Bioinoculants, such as free-living diazotrophs and rhizobia in a symbiotic relationship with plants, convert atmospheric nitrogen to an accessible form, particularly ammonia, a process called nitrogen fixation. This process is critical for plant growth and especially essential in agricultural sustainability, reducing the need for nitrogen fertilizers. Bioinoculants also mobilize potassium and phosphorus, which make them available for plants, leading to growth promotion and yield (Naamala and Smith, 2020). Bioinoculants synthesize siderophores that chelate and mobilize micronutrients, like manganese, zinc, and iron, which support plant health. Although these micronutrients are required in small amounts, they are important for plant resilience to extreme environmental conditions and growth. Nutrient cycling and uptake involve many physiological and biochemical processes that are influenced by the production of phytohormones, which control nutrient mobilization and uptake, root growth, and overall ability to alleviate environmental stress (Singh *et al*., 2018).

Phytohormone production and regulation

Bioinoculants advance the synthesis of phytohormones to stimulate plant growth and adaptation to stress. Phytohormones are signalling molecules that regulate various plant processes, such as germination and root and shoot growth, which are important for growth and stress response. Phytohormones trigger signal pathways that activate stress responses such as antioxidant enzyme production and stomatal closure during drought, helping plants tolerate climate challenges. Phytohormones like auxin, cytokinin, gibberellins, ethylene, salicylic acid, brassinosteroids, and jasmonic acid play a critical role in promoting tolerance to abiotic stresses such as salinity, drought, and extreme temperature. Some strains of *Pseudomonas* and *Bacillus* produce the plant growth regulator ethylene, which can stimulate the formation of aerenchyma, hence improving root oxygenation and protecting the root against damage during waterlogged circumstances caused by floods or extreme rainfall (Harman *et al*., 2021). Bioinoculants modulate the production of phytohormones and signalling, which leads to enhanced plant growth and yield under different biotic and abiotic stresses. The bioinoculant-mediated plant responses to abiotic and biotic stresses are highlighted in Fig. 2.

Abiotic stress mitigation

Bioinoculants are abiotic stress mitigators; they play a critical role in CSA by alleviating the impact of shifts in climate on crops. Some microbial strains used in bioinoculants have the functional ability to tolerate abiotic stresses, for example, extreme temperature and drought. Inoculating plants with these stress-tolerant microbial strains could improve resilience in plants to climate change-induced stresses, thus boosting crop yields in the face of harmful environmental conditions (Igiehon and Babalola, 2017; Rahman and Zhang, 2018). The application of bioinoculants on seedlings before planting can stimulate the production of antioxidants, heat shock proteins (HSPs), and compatible solutes in plants, which aid in protecting cellular structures and enzymes from adverse impacts of high- or low-temperature stress. Mitra *et al*. (2021) reported that *Bacillus amyloliquefaciens* NBRI-SN13 (SN13) positively regulated stress-responsive gene expressions under different abiotic stresses,

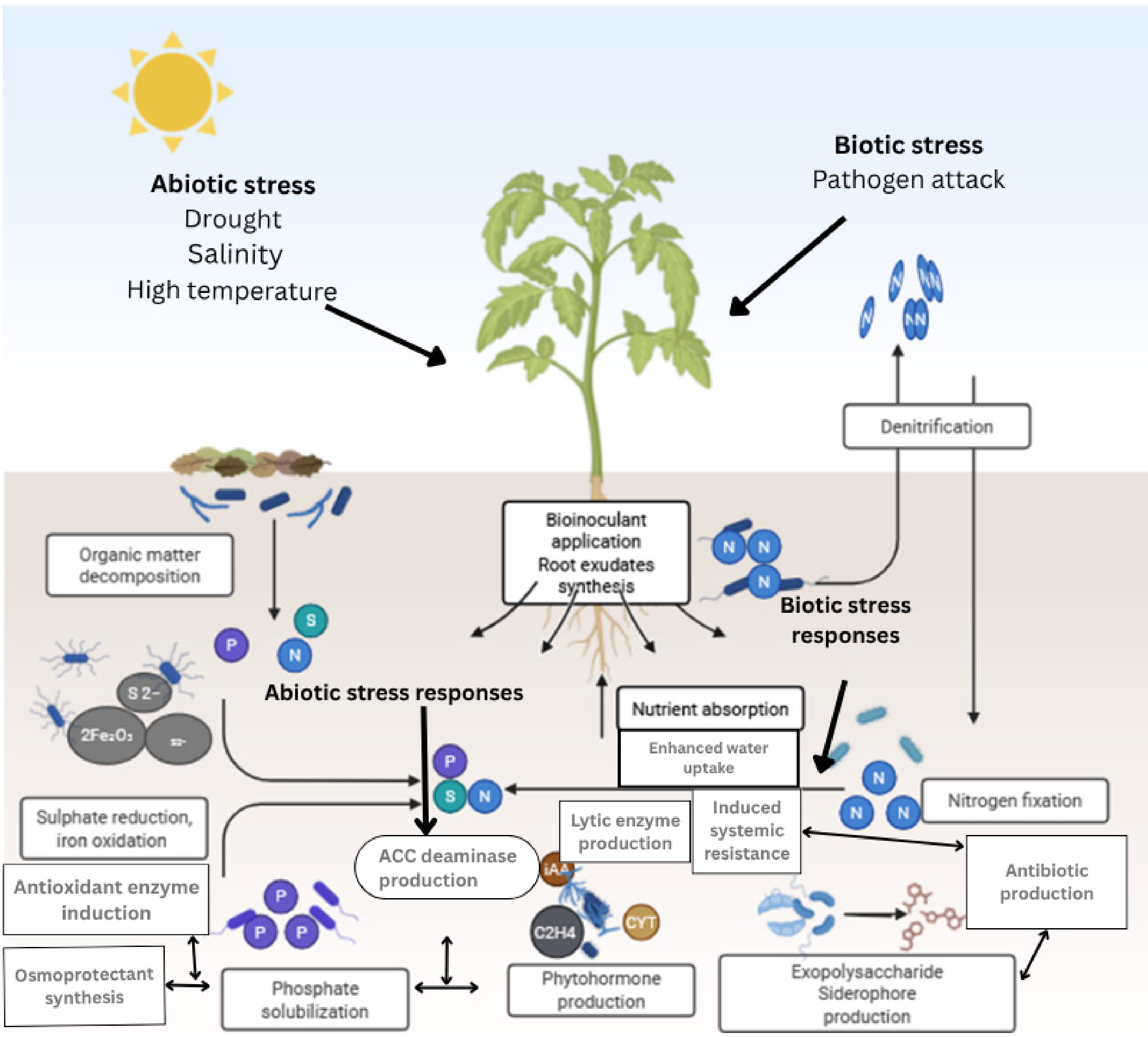

Fig. 2. Bioinoculant-mediated plant responses to abiotic and biotic stresses (Figure created and modified using BioRender, an online tool).

including cold, heat, freezing, drought, desiccation, and salt, as well as phytohormone treatment on rice cv. Saryu, which propose its versatile functions in stress responses. Similarly, sorghum seedlings inoculated with *Pseudomonas* sp. AKM-P6 showed greater tolerance against heat stress due to the buildup of HSPs (Mitra *et al*., 2021).

Moreover, bioinoculants enhance root systems, leading to better water and nutrient acquisition in extremely hot environments. Zeboni *et al*. (2024) demonstrated that bioinoculants can significantly enhance the root systems of certain plant species, such as *Crithmum maritimum*. The application of bioinoculants resulted in notable improvements in root weight, diameter, and length, highlighting their potential to accelerate the domestication process of these species, water retention, and support agricultural practices in areas at risk of desertification. Generally, agriculture plays a critical role in greenhouse gas emissions, mainly through the utilization of synthetic fertilizers in farming. Bioinoculants offer a promising solution to alleviate these emissions by increasing nutrient utilization, improving carbon sequestration in soils, and advancing sustainable agricultural practices (Tetteh *et al*., 2021).

The growing demand for sustainable and environmentally friendly agricultural systems that mitigate environmental harm and promote biodiversity advancement is evident. Bioinoculants align with these principles by reducing dependence on synthetic inputs, promoting nutrient recycling, and supporting ecological functions. As climate patterns change, certain crops and farming practices may become less suitable in specific regions. Bioinoculants play a pivotal role in expediting crop adaptation to changing climatic conditions by increasing stress tolerance, aiding nutrient acquisition, and providing multiple stress mitigation mechanisms. Moreover, bioinoculants enhance the overall adaptability and resilience of crops to the unstable and unpredictable weather patterns associated with climate change (Bittencourt *et al*., 2023).

Bioinoculants enable farmers to reduce dependence on non-renewable resources. Studies have shown that the production of chemical fertilizers depends heavily on non-renewable resources, especially fossil fuels, for their synthesis and transport. Bioinoculants can be produced using renewable resources and locally available natural materials, reducing the carbon footprint of agriculture and promoting self-sufficiency (Antar *et al*., 2021; Duhan and Kataria, 2023). Bioinoculants have the potential to enhance climate-resilient agriculture by improving crop productivity and stability under changing climatic conditions, thereby supporting the objective of ensuring food security amid climate change (Mitra *et al*., 2021).

Exopolysaccharide (EPS) and siderophore production

Likewise, bioinoculants have been recognized to improve soil health by enhancing microbial diversity and interactions in the soil exposed to climate challenges compared to chemical fertilizers. They also increase soil organic matter content, improve soil structure, soil aggregation, and moisture retention, protect plants, and indirectly support solute accumulation in plant tissues from environmental stresses (Khan *et al*., 2021). The group of microorganisms such as PGPR and AMF, used as bioinoculants, produces exopolysaccharide (EPS) that helps plants tolerate different environmental stressors. EPS acts as a protective barrier against abiotic stresses such as drought, salinity, and extreme temperature. The EPS employs several mechanisms that facilitate nutrient uptake, water retention, immobilize harmful substances, and promote microbial interactions.

In drought conditions, the application of bioinoculants, especially PGPR that produce EPS, alleviates drought stress in plants by binding to water molecules, which form a protective layer around roots that enhances water availability. This mechanism helps plants tolerate prolonged drought by reducing water loss and protecting against desiccation (Naseem *et al*., 2018). Furthermore, EPS may play a critical role in osmotic adjustment, a physiological process in which plants accumulate solutes such as glycine betaine, proline, and sugars to balance water potential between the cytoplasm and the environment. This adjustment is important for sustaining cell turgor, membrane stability, and metabolic functions under stress conditions such as drought and salinity (Ali *et al*., 2024). Also, the application of bioinoculants, particularly PGPR that produce EPS, has shown potential in contributing to plant resilience under saline stress through various mechanisms. A major process is EPS-mediated salt exclusion, where EPS binds to the sodium ions in the soil, limiting their mobility and preventing them from entering the roots. This reduces toxicity effects, which can disturb the cellular homeostasis and physiological processes. By preventing root sodium ion uptake, EPS protects root cell membranes and contributes to ionic balance. EPS can help improve the uptake of essential nutrients, like potassium, improve enzyme functions, and maintain plant metabolism, which are important for plant growth under saline conditions. EPS not only mitigates the adverse impacts of saline stress but also promotes plant health and productivity in saline soils (Ahmed and Holmström, 2014; Ali *et al*., 2024).

Moreover, EPS also aids in plant resilience to extreme temperature stress. EPS stabilizes soil structure, retains moisture, and protects microbial cells and plant roots from temperature-induced damage through the formation of biofilms and insulation layers. This buffering effect enhances microbial survival and promotes plant-microbial interactions under thermal stress (Naseem *et al*., 2018). Besides EPS production, another important trait of bioinoculants is siderophore production. Siderophores are iron-chelating compounds secreted by microorganisms that promote the availability of iron to plants, especially in iron-deficient soils, thereby supporting critical metabolic and photosynthetic processes under both normal and stress conditions. Siderophore production is a significant functional trait of various bioinoculants, playing a crucial role in plant health, particularly under stress conditions. In iron-limited soils, common in both saline and alkaline environments, plants fail to acquire sufficient iron, an important nutrient for chlorophyll synthesis, enzyme activation, and respiration (Mahawar *et al*., 2023). Microorganisms that produce siderophores secrete low-molecular-weight compounds that sequester ferric iron (Fe^{3+}) with high affinity, solubilize it, and make it more available for plants. The functional characteristics of siderophores in nutrient acquisition and plant protection underscore their importance, particularly for plants grown in stressed soils (Ahmed and Holmström, 2014; Saha *et al*., 2016).

SOIL HEALTH IMPROVEMENT MECHANISMS

Bioinoculants greatly influence the formation of stable soil aggregates compared to chemical fertilizers, which may result in soil acidification, decreased microbial diversity, and long-term soil degradation (Kalia *et al*., 2020). Collectively, these effects demonstrate how bioinoculants improve soil structure and function, enabling better crop resilience under climate stress. Cheng *et al*. (2022) demonstrated that inoculation with *Funneliformis mosseae* significantly increased extractable and total glomalin-related soil protein levels under two soil water treatments (well-watered (75% of maximum water holding capacity) and drought stress (55% of maximum water holding capacity)). Such a marked increase facilitated soil macroaggregate (2–4 mm size) formation, thus improving soil aggregate stability in trifoliate orange. Unsustainable agrarian methods, such as the overuse of synthetic fertilizers, can result in soil degradation and nutrient reduction. Bioinoculants, like PGPR and AMF, have the potential to improve soil quality through improved nutrient cycling and nutrient availability. This is not usually achieved by the extensive use of chemical fertilizers. Therefore, their use can reduce the reliance on synthetic fertilizers and advance practices that support sustainable soil management (Shelke *et al*., 2023).

Bioinoculants are reportedly compatible with organic farming, as they do not introduce artificial chemicals into the agroecosystem.

These traits make bioinoculants invaluable tools for farmers who want to implement organic and sustainable farming approaches while maintaining crop productivity. In addition to these direct effects, bioinoculants can contribute to climate-adapted agriculture by advancing sustainable farming practices, reducing the need for synthetic inputs, and supporting soil health and biodiversity, which can further enhance the resilience of agricultural systems to climate variability and extremes. Through the integration of innovative approaches, such as bioinoculants, into climate-adapted agriculture, these processes can enhance crop productivity, resilience, and sustainability while mitigating the effects of climate change and promoting sustainable water and soil management practices (Antar *et al*., 2021). Bioinoculants are distinct due to their eco-friendly nature, specificity in action, and potential to improve soil health, which makes them a promising alternative to chemical fertilizers that is compatible with organic agricultural practices. Their ability enhances tolerance to abiotic stresses, confirming their potential role in climate change adaptation for agriculture. While challenges in the widespread adoption of bioinoculants remain, increasing evidence supports their roles as stress mitigators and sustainability enhancers in climate-smart agriculture (Shelke *et al*., 2023). Given the many advantages of bioinoculants over traditional chemical fertilizers, it is essential to examine the specific types of bioinoculants, such as mycorrhizal fungi (MF) and PGPR, to fully understand their potential for sustainable agriculture.

TYPES OF BIOINOCULANTS

The need for an innovative approach to suppress climate change-related challenges in agriculture has necessitated the use of bioinoculants. Bioinoculants are described as microorganisms that are introduced into an environment for purposes such as biocontrol, promoting plant growth, and as stress tolerance enhancers. These groups of bioinoculants are classified based on their primary functions, such as phosphate-solubilizing, nitrogen-fixing, zinc-solubilizing, and potassium-solubilizing bioinoculants (Gelvez-Pardo *et al*., 2023). Furthermore, bioinoculants are categorized depending on their nature as bacterial, algal, and fungal bioinoculants (Kaminsky *et al*., 2019). They are known to increase crop productivity by directly or indirectly enhancing plant development. They also serve as a renewable source of plant nutrients and promote sustainable agronomy (Backer *et al*., 2018; Maitra *et al*., 2021; Shahwar *et al*., 2023). Bioinoculants like the MF and the PGPR are of particular agricultural interest, and their mechanisms of action are outlined below.

Mycorrhizal fungi (MF)

It has been reported that using MF as a bioinoculant in the rhizosphere of natural plants is a good substitute for chemical fertilization techniques and is a potential component of sustainable agricultural systems. MF establish a mutualistic symbiotic relationship with plant roots, extending the root absorption area through their hyphal networks and enhancing access to water and essential nutrients such as phosphorus, nitrogen, and potassium (Sinha and Raghuwanshi, 2016; Zydlik *et al*., 2021). This symbiosis plays a key role in improving plant micronutrient uptake and contributes to agricultural biofortification strategies (Gelvez-Pardo *et al*., 2023). Moreover, MF can enhance plant tolerance to environmental stressors, including salinity (Otlewska *et al*., 2020), antagonistic soil bacteria (Weber, 2014), and phytopathogens (Akanmu *et al*., 2021). Inoculation of the plant with the fungus can trigger a positive response in plants. Increased performance was observed in soybean (Adeyemi *et al*., 2020), onion plant (El-Sherbeny *et al*., 2022), and upland cotton (Gao *et al*., 2020) after the application of MF inoculum and suboptimal dosages of phosphate.

In addition to enhancing crop productivity, MF associations can significantly improve crop quality by increasing the uptake of macro- and micronutrients. For example, MF interaction in soybean plants has been shown to increase nitrogen, phosphorus, and potassium levels, ultimately increasing both yield and nutritional quality (Sheteiwy *et al*., 2021). MF increase nutrient absorption through hyphal extension into the surrounding soil matrix, allowing access to water and essential nutrients beyond the reach of plant roots. These fungi are particularly effective in improving phosphorus availability, a nutrient that is often limited in agricultural soils.

MF enhance nutrient uptake efficiency for the plant. For example, sustainable food production allows plants to effectively utilize mineral elements such as phosphorus, nitrogen, and potassium. Often, although phosphorus is crucial for plant growth and development, it is limited in soil. MF can obtain sufficient supplies of phosphorus that are beyond the reach of plant roots from the rhizosphere; they do this by extending their hyphae into the soil and, in turn, increasing phosphorus levels in plants. MF interactions not only facilitate the acquisition of phosphorus and nitrogen but also contribute to the transport of sulfur to the host plant. This interaction leads to an enhancement in the host plant's sulfur nutritional levels, consequently triggering the upregulation of the plant sulfate transporter gene expression.

AMF can also contribute to better soil aggregation and water retention, reducing the impact of drought periods on plant growth (Leifheit *et al*., 2014). Leventis *et al*. (2021) observed that inoculating tomato plants (*Lycopersicon esculentum* cv. EVIA F_1) with consortia of two AMF strains, *Rhizophagus irregularis*, and *Funneliformis mosseae*, significantly improved tomato plant vegetative growth. Under well-watered conditions (70% water holding capacity), AMF colonization enhanced shoot dry weight by 40% ($p < 0.05$), while under water-limited conditions (30% water holding capacity), growth improvements reached 50–60% ($p < 0.05$). Under well irrigated conditions, AMF inoculation increased transpiration rates by an average of 68% (45% for *F. mosseae* and 91% for *R. irregularis*) and stomatal conductance by an average of 78% (56% for *F. mosseae* and 100% for *R. irregularis*) compared to non-inoculated controls (n = 5 per treatment, Duncan's multiple range test, $p < 0.05$). However, when irrigation was limited, AMF helped maintain the rates of stable transpiration and stomatal conductance while plummeting the leaf area-to-leaf biomass ratios.

MF have been observed to interact with beneficial bacteria such as plant growth-promoting rhizobacteria (PGPR). Co-inoculation with MF and PGPR can synergistically enhance nutrient cycling, promote early root colonization, and improve crop yields under abiotic stress conditions (Sagar *et al*., 2021). This strategy holds promise for resilient cropping systems, particularly under drought or in low-fertility soils. The potential of co-inoculation of these two organisms in promoting the growth of crops, like rice (Chen *et al*., 2023), strawberry (Emmanuel and Babalola, 2020), maize (Moreira *et al*., 2020), and spinach (Khalid *et al*., 2017), has also been reported and should be studied in terms of their holistic approach.

Plant growth-promoting rhizobacteria (PGPR)

PGPR promote plant growth by producing auxins and cytokinins, solubilizing phosphates, and inducing systemic resistance against pathogens (Table 2). These actions help plants withstand environmental stressors, especially those worsened by climate change (de Andrade *et al*., 2023; Hasan *et al*., 2024). Some PGPR bioinoculants can synthesize phytohormones, which can enhance soil structure and water-holding capacity (Bittencourt *et al*., 2023). Studies have shown that during plant-microbial interactions, there is regulation of the hormonal balance of abscisic acid (ABA), a typical stress hormone in plants specifically released during water deficit. Thus, they promote plant growth even under environmentally stressful conditions (Gupta *et al*., 2022; Kaya *et al*., 2023). For instance, Curá *et al*. (2017) established that inoculation with the bacteria *Herbaspirillum* and *Azospirillum* in maize plants directly influences physiological, biochemical, and molecular processes. Another study by Salomon *et al*. (2014) reported that PGPR (*Pseudomonas fluorescens* Rt6M10 and *Bacillus licheniformis*

Table 2. Mechanisms of action for PGPR and AMF.

	Methods	Descriptions	Effects	Microorganisms	Reference
PGPR					
Nutrient Acquisition	Nitrogen fixation.	N-fixing symbiosis between rhizobia and legumes.	Increased root growth. Increased access to soil.	*Azoarcus sp.*, *Burkholderia* sp., *Gluconacetobacter* sp., *Diazotrophicus sp.*, *Herbaspirillum* sp., *Azotobacter sp.*, *Bacillus polymyxa*, and *especially Azospirillum sp.*	Vessey (2003); Adesemoye and Kloepper (2009); Bashan and de-Bashan, (2015); Shakeel *et al*. (2015); Shanta *et al*. (2016)
	Phosphate-solubilization	The fertilization of crops with rock phosphate.	Increased dry matter and nodule number in inoculated plants. Plants can access the reservoir of non-labile phosphorus. Metal toxicity is reduced in plant tissues. The reduction of phosphate fertilizer requirement in crops.	Phosphorus solubilizing microorganisms (PSMs): strains of P- solublizing *Pseudomonas striata*, *B. Polymyxa*, and *B. megaterium*.	
	Organic acid production.	Solubilizes Fe through organic acid production	Control pathogenic microorganisms Increase yield in several crops, including rice, wheat and soybean.	*Acidithiobacillus ferrooxidans*	
Signal exchange between plant roots and PGPR	Production of plant hormones by PGPR e.g. Auxins, Gibberellins, cytokinins, Jasmonins, Salicyclic acids, etc.	Production of phytohormones which function as molecular signals in response to environmental factors.	Boost growth and stress response. Regulate plant growth and development. Increase root biomass and decrease stomata size and density.	*Enterobacter sp.*, *Arthrobacter sp.*, *Rhizobium sp.*, *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Azospirillum sp.*	Afzal *et al*. (2015); Kenneth *et al*. (2019); Pantoja-Guerra *et al*. (2023)
	Microorganism-to-plant Signal molecules e.g. polyamines, spermidine.	The production of secondary metabolites and volatile organic compounds (VOCs).	Increased shoot biomass, altered root architecture, and elevated photosynthetic capacity. Improves stress tolerance and/or stimulates growth in plants.	*B. megaterium*, *Rhizobium leguminosarum* *Arabidopsis thaliana*.	Prasad (2023); Zulfiqar *et al*. (2023)
	Roots exudation	Manipulation of root-associated microbiota. Exudates consisting mainly of sugars, amino acids, organic acids, flavonoids, terpenes, and phenolic compounds attract specific microorganisms in the rhizosphere.	Increased microbial growth and activity in the rhizosphere. Nutrient cycling, soil aggregation, and disease suppression. Root exudates increase the transport and metabolism of nutrients.	*Arthrobacter* sp., *Rhizobium* sp., *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Azospirillum* sp.	Feng *et al*. (2023); Han *et al*. (2023); Zhang *et al*. (2023)

AMF					
	Improvement of macro and micronutrients	Application of AMF directly to plants triggers a positive response in plants.	Increased crop quality and crop productivity.	*Glomus mosseae* (also known as *Funneliformis mosseae*), *Gigaspora margarita*.	Adeyemi *et al*. (2020); Gao *et al*. (2020); El-Sherbeny *et al*. (2022)
	Nutrient uptake efficiency	AMF obtain sufficient supplies of phosphorus that are beyond the reach of plant roots from the rhizosphere by extending their hyphae into the soil. AMF transports sulfur to the host plant, thereby increasing the host plant's sulfur nutritional levels.	Increased phosphorus level in plants. Triggers the upregulation of the plant sulfate transporter gene expression.	*Rhizophagus irregularis (formerly Glomus intraradices)*, *Glomus mosseae* (also known as *Funneliformis mosseae*), *Claroideoglomus etunicatums*	
	Interaction with beneficial bacteria e.g. PGPR	Synergistic association of both AMF and PGPR in plants.	Improved nutrient and water uptake, better root development, and increased resistance to pathogens and environ-mental stresses.	Glomus mosseae (also known as Funneliformis mosseae), *Claroideoglomus etunicatums)*	Emmanuel and Babalola (2020); Moreira *et al*. (2020); Chen *et al*. (2023)

Rt4M10) inoculation creates the buildup of indole-3-acetic acid (IAA), abscisic acid (ABA), and the gibberellins A_1 and A_3 in Vitis vinifera cv. Malbec plants.

PGPRs can either directly or indirectly enhance plant development. They can do this by deploying mineral nutrients in soils to promote plant growth, controlling or inhibiting phytopathogens, producing different plant growth regulators, enhancing soil structure, and bioremediating the soil by removing noxious heavy metals and reducing chemical compounds like fungicides and pesticides. Numerous bioinoculants of PGPR species, including *Azospirillum*, *Bacillus*, *Rhizobium*, and *Pseudomonas*, can stimulate the synthesis of osmoprotectants, siderophores, EPS, and stress-related proteins in plants (Naseem *et al*., 2018; Ahmad *et al*., 2022). Also, some enzymatic antioxidants, such as catalase, glutathione reductase, ascorbate peroxidase, and superoxide dismutase, as well as nonenzymatic antioxidants, including ascorbate, α-tocopherol, glutathione, flavonoids, and phenolic compounds, protect the plants from oxidative damage (Nivetha *et al*., 2021). These processes aid in maintaining the water balance in plants, protect cellular structures, and alleviate drought stress (Sarker *et al*., 2021). As climate-induced stresses such as drought and heat become more frequent, the deployment of PGPR offers a climate-resilient strategy for stabilizing crop yields (Hyder *et al*., 2023).

Applications of bioinoculants

BIOINOCULANTS OVER CHEMICAL FERTILIZER

The successful use of the MF and PGPR as bioinoculants has proven that they are highly beneficial in enhancing agricultural sustainability; hence, they are gaining significance in the field of agriculture and environmental sustainability. The use of bioinoculants has drastically reduced the use of chemical fertilizers (Scagliola *et al*., 2021). Currently, there are a significant number of bioinoculant businesses operating across several geographical regions (Shahwar *et al*., 2023). In South Africa, government agencies such as the Agricultural Research Institute and the Department of Agriculture, Forestry, and Fisheries oversee inoculant production. These include products, including bioinoculants and biopesticides, marketed as alternatives to synthetic inputs (Raimi *et al*., 2021).

Furthermore, the overuse of agrochemicals has had a disastrous effect on the environment, human health, and animal welfare (Nicolopoulou-Stamati *et al*., 2016). This was particularly evident in certain impoverished areas. However, field applications of bioinoculants have led to improved soil fertility, higher crop yields, and reduced dependency on agrochemicals, particularly in resource-constrained farming systems (Khandare *et al*., 2020). Table 3 represents bioinoculant applications, impacts, and study types.

DATA FROM FIELD STUDIES

Increased crop yield and crop quality have been observed with the use of bioinoculants (Maitra *et al*., 2021; Orozco-Mosqueda *et al*., 2021). A study conducted by Schütz *et al*. (2018) on the impact of bioinoculants across all crop categories showed an average yield increase of 16.2 ± 1.0% on inoculated crops compared to non-inoculated controls. Similarly, Li *et al*. (2022) reported an increase in crop yield with *Pseudomonas* (49.94%), *Enterobacter* (27.55%), and *Bacillus* (25.66%) as inoculants. These testimonies positively impact the economy, as they lead to farmers reducing input costs, which translates into farm profitability. The continuous supply of cheap food in these communities serves as proof of ecological balance and food security goals; these economic benefits contribute to the support of rural livelihoods, making them an adaptable tool for sustainable agriculture.

Studies have shown that the biofertilizer, also referred to as bioinoculants, is growing exponentially. In 2016, the global biofertilizer market was valued at US$1.06 million, while in 2018, the market value increased to US$1.57 billion and is expected to increase at a compound yearly growth rate of 12.1% between 2022 and 2027, reaching more than US$3.8 billion by 2027 (Intelligence, 2022). The recent surge in demand for organic products has significantly impacted the worldwide demand for plant growth. Biofertilizers (bioinoculants) are a safe technique, economical, and ultimately boost crop productivity. Metadata of percentage change of crop yield in response to bioinoculant application of diverse categories is as shown in Fig. 3.

Role of bioinoculants in increasing crop yields and resilience to climate change

The use of bioinoculants in agriculture is closely linked to climate change resilience, as they contribute directly and indirectly to both mitigation and adaptation strategies (Kumar *et al*., 2022a, b). Climate anomalies, which include irregular rainfall, drought, and extreme temperatures, are increasingly disrupting agricultural productivity and threatening food security (Grigorieva *et al*., 2023). These challenges are compounded by unsustainable practices such as excessive pesticide use, intensive tillage, and indiscriminate application of agrochemicals, which further accelerate climate change and environmental degradation.

Furthermore, the majority of plants are unable to adjust to the swift changes in ecosystems brought about by climate change soon enough. A serious threat to food security was posed by the rising temperatures in the late 20th century, which resulted in a global decrease in the production of staple grains like wheat, rice, and maize as well as an increase in food consumption (Kumar *et al*., 2022a, b). These historical events align with current projections by the IPCC (Intergovernmental Panel on Climate Change); the projected climate change patterns adversely impact all four pillars of food security, including availability, accessibility, utilization, and stability, and their interactions (Mbow *et al*., 2017). According to the Food and Agriculture Organisation (FAO) and World Food Programme (WFP), acute food insecurity is expected to worsen across 13 countries across Africa, Asia, the Middle East, and the Americas, identified as hotspots in the short term (Boliko, 2019; Citaristi, 2022). The Organization for Economic Co-operation and Development (OECD) and FAO Agricultural Outlook 2024–2033 project that the increase in calorie intake in low-income countries is projected to be approximately 4%, which is an indicator of the persistent susceptibility of global food systems (OECD and FAO, 2024; Bellmann, 2025). Given these adverse effects of climate change, there is a need to assess the potential of bioinoculants, gathering information on the various functions that can help resolve the problems associated with modern agriculture and climate change.

Current challenges, limitations, and future prospects for bioinoculants in CSA

While the use of bioinoculants has been met with so much success as discussed above, this technology is not without its limitations. One of the major challenges to the widespread adoption and the use of bioinoculants is that after being incorporated into the soil, bioinoculants encounter competitive environments that could significantly diminish their advantageous impacts. Though, as previously mentioned, the application of bioinoculants has been incredibly successful, this technique is not without its drawbacks. A primary obstacle to the extensive implementation and application of bioinoculants is their competition with the soil flora. Additionally, despite the current understanding of the functional features of the interactions between microorganisms and plants and how these interactions affect plant growth, farmers in certain parts of the world, particularly in industrialized areas, are still slowly adopting these products (Elisabeth *et al*., 2019). They are still in their infancy

Table 3. Bioinoculant applications, impacts, and study types.

Bioinoculant	Plant	Stress mitigated	Mode of inoculation	Effects	Study type	Economics	Reference
Trichoderma viride, *Glomus mosseae*, and *Gigaspora gigantean*	Vicia faba (Faba bean)	Salinity	Seed	Increases plant height, leaf area, shoot length, number of pods (48.33 count) and branches (4.87 count) per plant	Field	33.21grain yield in grams per plot	Kumar *et al*. (2022)
Pseudomonas fluorescens, *P. putida*, *B. subtilis*	Vicia faba	Salinity	Soil	Increased plant height, fresh weight, and leaf area	Greenhouse	Increased the fresh and dry shoot and root masses.	Mohammed *et al*. (2020)
Bacillus subtilis, *Pseudomonas fluorescens*	Radish plants (Raphanus sativus)	Salinity	Seed	Root dry weight (~1.4–1.6 g/plant)	Greenhouse	Increased biomass over 100% NaCl levels and root yield	Mohamed and Gomaa (2012)
Efficient Microorganisms (EM) Mixture, composed of *Bacillus subtilis* nato B/23-45-10, *Lactobacillus bulgaricum* B/103-4-1, and *Saccharomyces cerevisiae* L-25-7-12	Phaseolus vulgaris (bean) cultivars: Velazco Largo (VL) and Cuba Cueto (CC-25-9-N)	Abiotic (yield, water)	Foliar, soil, or combined	Pods per plant (110–145%) and yield (97–239%)	Field (block trial)	Yield increased up to 2.15 t/ha	Calero Hurtado *et al*. (2019)
Bacillus subtilis, *Pseudomonas fluorescens*	Faba bean (Vicia faba L.)	Salinity	Seed	Increased pods per plant (43–62%)	Greenhouse	100-grain weight per plant	Metwali *et al*. (2015)
Virgibacillus marismortui, *Alkalibacillus haloalkaliphilus*	Triticum aestivum	Salinity	Soil and seed	Fresh wt of shoots, ears, stems ↑~2x;	Greenhouse	Grain yield increased up to 15%	Torbaghan *et al*. (2017)
Bacillus cereus strain Bc-cm103	Cucumber (*Cucumis sativus*, cultivar Zhong-nong 6)	Biotic: Root-knot nematodes (Meloidogyne spp.)	Root, soil, and irrigation	Reduced nematode infection and root galling. Significant increase of shoot growth and induced plant defense gene expression (SA and JA pathways)	Hydroponic, greenhouse, and field	Field yield increased by 14% (2018) and 75.62% (2019) compared to untreated control	Yin *et al*. (2021)

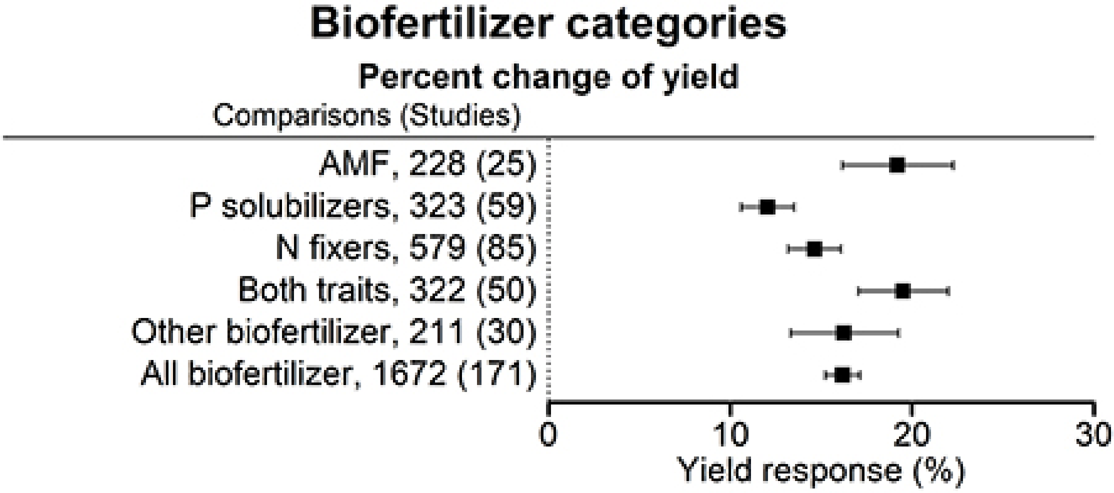

Fig. 3. Metadata of percentage change of crop yield in response to biofertilizer application of diverse categories (Schütz *et al.*, 2018). A summary of mean values and 95% confidence intervals of the back-transformed reaction ratios. A more prominent impact with Arbuscular Mycorrhizal Fungi (AMF) and for Nitrogen (N) fixers with P (Phosphorus) solubilizers was observed.

in Europe, although they are widely distributed in Asia and Latin America (Barquero *et al.*, 2019). Both host plant- and strain-specific processes may be implicated in plant promotion. Thus, the advantages of applying a particular bioinoculant may vary significantly depending on the agro-environmental circumstances, which has led to controversies about the effectiveness of microbial-based products (Owen *et al.*, 2015; Malusà *et al.*, 2016).

Numerous other variables can also have an adverse impact on bioinoculants, including tillage-induced disruption of hyphal networks, as well as crop variety selection through breeding (Berdeni *et al.*, 2018; Li *et al.*, 2019; Chakraborty and Akhtar, 2021). A gap is also present in the way inoculants are prepared and administered. The primary cause of this is the incapacity of the inoculant manufacturers, who are primarily located in industrialized nations, to account for the difficulties that arise when the inoculants are used in developing nations, which constitute most of their intended market (Malusà *et al.*, 2016; Amenaghawon *et al.*, 2021). Other drawbacks include farmers' and extension workers' inadequate comprehension of the inoculation procedure, low-quality inoculants produced, inefficient inoculant delivery and supply systems, inadequate farmer education and sensitization regarding the use and advantages of bioinoculants, and a lack of coordinated policy efforts to guarantee the use of bioinoculants (Thomas and Singh, 2019).

FACTORS PRECLUDING THE ADOPTION OF BIOINOCULANTS

In some regions of the world, like the USA and Canada (Orozco-Mosqueda *et al.*, 2021) and South Africa (Raimi *et al.*, 2021), various types of soil microorganism taxa based on the cellular organization are categorized as prokaryotes (bacteria and archaea) and eukaryotes (fungi, algae, and protozoa) and can be used to produce microbial-based fertilizers (bioinoculants). Choosing the right microbial strain or strains to produce bioinoculant can be somewhat tasking. In addition to having a wide host range, the strain(s) should not be particularly focused or selective (to certain crops). Their selectivity is a major limiting factor (Vejan *et al.*, 2016). The viability of the strain must also be considered. When treated as spores, some strains, like those of the *Bacillus* species, have a longer shelf life. However, certain strains, particularly non-sporulating types, require specific formulations to maintain viability until inoculation (Ngo *et al.*, 2019).

Moreover, a preliminary screening in a laboratory is necessary before a novel PGPR strain can be developed as a successful bioinoculant. This process is dependent on the direct and indirect processes of PGPRs that promote plant development. Under field conditions, effective plant growth promotion is not guaranteed by merely primary screening axenic culture isolates for PGPR characteristics. In addition, pure culture isolates with lower levels of *in vitro* growth-promoting activity may have distinct techniques for encouraging plant development. Such isolates show difficulties in screening under conventional settings, perhaps due to an incomplete understanding of their mechanisms. As a result, occasionally these beneficial strains are rejected because of their subpar *in vitro* performance (Basu *et al.*, 2021).

In addition to the factors, the primary aspects are a lack of understanding of the relationships between microorganisms and plants, poor acceptance by regulatory bodies and other stakeholders, lack of availability, high cost, low farmers‘ literacy level, poor storage conditions and facilities, unpredictable results, and difficulties in identifying and tracking inoculated strains in the field (Backer *et al.*, 2018; Jabborova *et al.*, 2020; Meena *et al.*, 2020). The development and commercialization of bioinoculants face challenges due to bureaucracy. Regional and national marketing regulations frequently differ. The distribution of goods can occasionally entail a chain of inexperienced personnel who may mishandle the products. Low- or poor-quality bioinoculants could result from the microorganisms used as bioinoculants being exposed to high temperatures (over 40°C) throughout this process, which could cause them to either inactivate or die. Going forward, the farmers and the overall crop output will suffer from these inferior packets (Basu *et al.*, 2021).

The results of bioinoculant technology are determined by the two components of microbial strain and inoculant formulation. In practical terms, a formulation may change depending on the use of the bioinoculant, the kind of soil, the kind of plant, how it is applied, and the available resources (Fages, 1992). Because the strains of microorganisms utilized share many physiological features, technological advancements in the formulation are not influenced by these differences. Under such circumstances, technology developed for one strain can be applied, with only modest adjustments, to other strains that are related (Bashan, 1998). Presently available bioinoculant technologies comprise bacterial biofilm, phosphate (P) solubilizers, P mobilizers, nitrogen (N) fixers, PGPR, and biocontrol agents, such as bio-nanotechnologies (Malusá *et al.*, 2012; Sahu and Brahmaprakash, 2016). Despite these technologies' benefits and success stories, some of their main drawbacks include, among other things, the high cost of polymer-based carriers, the requirement for handling expertise, low oxygen transfer, which limits the inoculum's ability to survive, a lack of efficient inoculant delivery/supply systems, and low nutrient availability, particularly P, which influences biofilm adhesion to cells.

REGULATORY CONCERNS

Registration complexity

The necessity of registering bioinoculants remains difficult in many nations due to complex and comprehensive documentation requirements (Keswani *et al*., 2019; Raimi *et al*., 2021). Although product registration fees vary from region to region, they are generally on the higher end, and the regulatory procedures are very intricate (Meena *et al*., 2020; Aloo *et al*., 2021). The fact that biopesticides are treated in a similar manner as chemical pesticides in some places, such as India, is another significant barrier to their registration and market penetration (Desai *et al*., 2016).

Expertise and data limitation

The random use of synthetic pesticides in agriculture and related industries has led to contamination of the environment, including soil and water, which has resulted in diseases in humans and animals as well as a depletion of biodiversity. Additionally, the farming community began using chemical pesticides indiscriminately with the goal of minimizing losses from biotic stresses. This was also caused by a lack of knowledge regarding the specificity of the chemical molecules in synthetic pesticides against various insect pests and infections. Because of this, diseases and insects have developed resistance to these chemicals (Robert, 2013). Moreover, highly skilled and knowledgeable subject matter specialists are required by the regulatory bodies for the registration and examination of data about bioinoculants. Experts in regular registration who handle traditional pesticide data find it difficult to handle sophisticated biopesticide data due to a lack of thorough scientific understanding.

ENVIRONMENTAL CONCERNS

Safety is the primary concern when it comes to environmental issues around the usage of bioinoculants. Some of the microbial strains used in their manufacture pose health risks (Kumari *et al*., 2022). The World Health Organisation divided microorganisms into several risk groups (RG) according to certain criteria such as pathogenicity and virulence, host range, method of transmission, availability of treatments, and vaccinations for effective prevention. As a result, the classification – for example, risk group (RG)-1 to RG-4 – defines the degree of risk that a specific microorganism poses. *Comamonas* sp., a strong candidate for PGPR, is also linked to some serious conditions, including endocarditis and septicemia in immunocompetent people (Ryan *et al*., 2022). Human tissue structure can be altered by *Streptomycetes* sp., which can result in disorders like cancer, mycetomas, and actinomycetomas (Herbrík *et al*., 2020). In their study, Albright *et al*. (2020) reported a shift in the resident-flora population. Similarly, Walsh *et al*. (2003) observed a decrease in the rhizobacterial community when an antibiotic medium, 2,4-diacetylphoroglucino-producing bacteria, was applied in the rhizosphere.

Potential strategies for solving current challenges

Climate change impacts agroecosystem functions and services, and microbial inoculation can be a crucial strategy to lessen and ameliorate the adverse effects. The impacts of microbial inoculants are multifaceted, encompassing their direct effects as well as multiplier effects facilitated by the plant, microbial, or ecological levels (Singh *et al*., 2023). Although bioinoculants that are resistant to multi-stress are presently under development and have demonstrated encouraging outcomes in stressful environments, their large-scale commercialization has not been executed appropriately. Hence, impeding their accessibility (Ali *et al*., 2022). The ability of bioinoculants to withstand many pressures can be utilized to address the stresses encountered in contemporary agriculture, given the ever-changing environment and the growing worry over global warming (Kavadia *et al*., 2020).

With regard to the factors that contribute to the challenges, limitations, and concerns about the use and application of bioinoculants, especially in developing countries, it is pertinent to guarantee a greener future. This includes short-term interventions such as raising widespread public knowledge of the benefits of employing microorganism-based bioinoculants and educating both farmers and consumers (Nosheen *et al*., 2021). To educate and inspire farmers, a robust programme of awareness and training could be started. It is important to hire skilled workers and provide them with the necessary training as well. In addition, long-term programmes, including government action in the form of purposeful sponsorship of companies engaged in the research and manufacturing of bioinoculants, can help to lessen these difficulties. The relevant governmental organizations should also establish policies and guidelines on bioinoculants. Furthermore, promoting public-private partnerships can result in significant investment in bioinoculants and a rise in the supply and demand for the product (Raimi *et al*., 2021).

PROSPECTIVE BIOINOCULANTS IN CLIMATE-SMART AGRICULTURE

Investigations into the production and composition of bioinoculants could have a significant positive impact on their trade. Future applications of bioinoculants are probably going to be increasingly common as dormant components at lower costs are found for different formulations and application techniques advance. A new field of study was suggested when novel adjuvants were introduced and demonstrated a considerable increase in microbial activity. The choice of an appropriate formulation may improve the stability of the product, give it a longer shelf life, and improve the performance of the bacteria in the field (Keswani *et al*., 2016).

Moreover, as drought and waterlogging are predicted to be the two main issues in the future, molecular methods must be employed to modify and incorporate microorganisms that can withstand both conditions in plant systems. More researches can be performed on the latest ideas of the core microbiome, multi-species microbial biofilms, microbial-based volatiles, and rhizo-engineering to improve soil-plant-microorganism interactions and improve plant and soil health (Velmourougane and Prasanna, 2023). Accelerating crop productivity fast and sustainably may be best achieved by utilizing microbial inoculants in an integrated approach that minimizes chemical use. The growing emphasis on organic farming in recent times has brought attention to the important and wide-ranging function that microbial inoculants can play (Velmourougane and Prasanna, 2023).

NEED FOR NEW TECHNOLOGIES IN BIOINOCULANTS

As a form of live fertilizer known as "biofertilizer or" "bioinoculant," researchers have discovered and employed a variety of naturally occurring bacteria for sustainable crop production. Bioinoculants do not contribute to environmental pollution, making them environmentally friendly since they are products that use natural resources (Anuradha and Singh, 2021). Additionally, the surface area of the roots is increased when mycorrhizal bioinoculants are applied. Plant feeding with phosphate is greatly aided by *vesicular arbuscular mycorrhizal* (VAM). As a result of the ground's increased ability to absorb water and mineral salts, production rises.

To ensure market viability, cheap carrier materials that offer a more economical product for farmers compared to chemical fertilizers must be used to produce bioinoculants. According to Santos *et al*. (2019), humus and sugarcane residues, both of which are abundant, have been utilized. Moreover, the application of bionanotechnologies, nanoparticles, and nanostructures can be used as carriers of bioinoculants (Duhan *et al*., 2017; Adetunji *et al*., 2019). Future studies should explore, adopt, and integrate nano-applications for the advanced efficacy and market viability of various bioinoculants**.** A key factor to consider when planning a future course of study for bioinoculant research is the storage conditions. Maintaining appropriate storage procedures is a step towards producing a quality product that ensures the successful use of bioinoculants (Malusà *et al*., 2016). Moreover, innovative techniques such as encapsulation in biodegradable polymers, precision delivery via seed coating, and synthetic biology-based custom strains may be adopted. Furthermore, ongoing efforts to identify strains and screen for their effectiveness in various soil types, agroclimatic conditions, and farming scenarios are crucial. Understanding the dynamics of the inoculum under varied agronomic conditions in the field could help build a bioinoculant suitable for diverse crop physiological phases and farming techniques (Meena *et al*., 2020; Basu *et al*., 2021).

Conclusions

This review has significantly investigated the functionality of bioinoculants in climate-adapted smart agriculture, dealing with the query of whether the present publicity surrounding their usefulness is justified. Bioinoculants, particularly AMF and PGPR consortia, offer proven strategies to improve plant resilience, optimize nutrient cycling, and reduce the carbon footprint of agricultural systems. Bioinoculants' promising benefits are significant, including the enhancement of soil health and fertility through the addition of nutrients, mobilization, and solubilization. Also, many bioinoculants improve plant growth and help suppress plant pathogens. They can induce stress tolerance in host plants through diverse mechanisms, such as reactive oxygen species (ROS) scavenging, enhancement of antioxidant enzyme activity, modulation of stress-responsive gene expression, and production of osmoprotectants, like trehalose and proline, which is a critical factor in acclimatizing to climate change. Nevertheless, the efficacy of bioinoculants faces many challenges, and their functioning can vary across various environmental conditions. Thus, they must compete with resident soil microorganisms. The inconsistency in their effectiveness under varied climatic regions remains a concern for extensive acceptance. Notwithstanding these limitations, the potential for bioinoculants in climate-adapted smart agriculture is promising. As the awareness of the use of bioinoculants increases and research progresses, agriculturists are gaining a deeper knowledge of how to optimize their use in myriad agricultural systems. The advancement of more effective and resilient bioinoculant strains, coupled with enhanced application approaches, could extensively boost their dependability and effect. In summarily, while the hype around the benefits of bioinoculants may be slightly exaggerated, their potential to contribute sustainably to CSA is substantial. With further validation and investment, bioinoculants have the potential to transition from niche use to mainstream agricultural inputs in CSA strategies. Extensive research aimed at overcoming present limitations and challenges and exploring new applications will be imperative. By tackling these limitations, bioinoculants can play a dynamic role in creating resilient, prolific, and eco-friendly agricultural systems capable of adapting to our shifting climate.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

ETHICS STATEMENT

Ethical consent is not applicable.

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AUTHOR CONTRIBUTIONS

BCI contributed in conceptualization, data curation, visualization, writing-original draft, and writing-review and editing; BOO performed data curation, visualization, writing-original draft, and writing-review and editing; DJA contributed in data curation, visualization, writing original draft, writing review, and editing; ONI performed validation, writing review, and editing; and TS contributed in conceptualization, supervision, validation, writing-review, and editing. All authors read and agreed to the published version of the manuscript.

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