Overview of insights into the role of *Bacillus* species in drought stress alleviation and plant disease management

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Abstract. Drought and plant diseases are major constraints on crop production, causing significant losses. As the effects of climate change worsen, there is an urgent need to adopt sustainable agricultural strategies. Plant Growth-Promoting Bacteria (PGPB) are emerging as a promising approach, aimed at enhancing productivity and plant resilience to various stresses. Among them, *Bacillus spp.*, are gaining research interest due to their unique ability to adapt to harsh environmental conditions and produce metabolites of interest in several sectors. Besides improving plant growth and yield, *Bacillus* plays a pivotal role in enhancing the ability of plants to withstand drought stress mainly by producing water absorbing substances and enhancing water and nutrient uptake. Some *Bacillus* species are able to effectively resist plant pathogens through several mechanisms, including antibiosis, competition, induced systemic resistance (ISR), and enriching the microbiome of the soil, enabling them to become important biological agents in the management of plant diseases. This overview aims to highlight the potential of *Bacillus* species in sustainable agriculture, focusing on their role in mitigating drought stress and controlling plant diseases.

Keywords. *Bacillus* spp., drought stress, phytopathogens, Biocontrol, Plant Growth promoting Bacteria (PGPB).

1 Introduction

Climate change, with its manifestations such as rising temperatures, changing precipitation patterns and the intensification of extreme weather events, poses serious challenges to global agriculture [1-7]. These phenomena are exacerbating drought problems, making vast expanses of once-fertile land less productive and even unsuitable for agriculture [8]. Drought is not just a lack of water for crops; it also reduces the availability of nutrients in the soil, affects beneficial micro fauna and can lead to an increase in soil salinity, further reducing the ability of plants to grow and develop [9, 10]. Not only does drought reduce crop yields, it also directly affects the quality of agricultural produce, impacting the food chain at several levels [11,12]. Plant diseases are another misfortune in agriculture, resulting in considerable annual losses in crop yield. Infectious pathogens responsible for plant diseases not only decrease food production but also hinder economic development and ecological stability [13]. Historically, plant diseases have had devastating impacts, leading to starvation and the deaths of millions. An illustrative example is the Irish Potato Famine, which was caused by the plant pathogen *Phytophthora infestans*. This pathogen causes late blight, a severe disease affecting potatoes. In efforts to maintain disease-free agriculture, reliance on pesticides is common; however, this strategy often results in harmful environmental consequences. *Bacillus* species, a group of bacteria found in soil, are emerging as promising agents in this quest. Known for their ability to promote plant growth, improve crop resistance to environmental stresses and combat a variety of pathogens, these microorganisms offer an alternative to conventional agricultural management methods, often costly and harmful to the environment [14-16]. Thanks to their varied mechanisms of action, which include the production of antimicrobial compounds, the induction of plant resistance and the enhancement of water and nutrient uptake, *Bacillus* are positioned at the heart of sustainable agricultural development strategies [17, 18]. The aim of this study is to provide a comprehensive overview of recent research into the role of *Bacillus* species in drought mitigation and plant disease management. We will examine the mechanisms by which these microorganisms benefit agriculture, highlighting case studies and experimental results that demonstrate their efficacy. By exploring the breadth of current knowledge, this review aims to highlight the potential of *Bacillus* as biotechnological tools in improving crop resilience. Through this analysis, we hope to contribute to the dialogue on sustainable approaches in agriculture, offering new perspectives for the development of integrated drought and plant disease management strategies.

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2 Bacillus species: an overview

Bacillus species represent a genus of bacteria that play a crucial role in a variety of environments, particularly in soil, where they exert a significant influence on plant health and growth [19, 20]. Characterized by their ability to form spores, these bacteria are remarkably resistant to adverse environmental conditions, such as extreme heat, drought or the presence of chemical disinfectants [21]. This resilience is due to their unique life cycle, which enables them to subsist as dormant spores for extended periods, only to return to an active form when conditions become favourable. Morphologically, Bacillus are Gram-positive bacteria, meaning they have a thick cell wall composed mainly of peptidoglycan [22]. They generally take the form of rods and are able to move thanks to the presence of flagella, giving them a mobility that facilitates their dissemination in the environment [23]. Ecologically speaking, Bacillus are essential decomposers, actively participating in the breakdown of dead organic matter and thus contributing to soil fertility. But their role doesn't stop there: several Bacillus species are known for their ability to produce substances beneficial to plants, such as enzymes, growth hormones and natural antibiotics that can protect crops against various pathogens. What's more, some strains have the ability to establish symbiotic relationships with plants, promoting nutrient uptake and enhancing plant tolerance to abiotic stresses such as drought or salinity [24]. In agriculture, interest in Bacillus has grown considerably due to their potential as biofertilizers, biopesticides and biocontrol agents. These applications reflect a more sustainable and environmentally-friendly approach to crop management, reducing dependence on chemical fertilizers and synthetic pesticides, whose excessive use is associated with public health problems and negative impacts on ecosystems [25].

Research into Bacillus and their application in agriculture continues to develop, paving the way for innovative strategies to improve agricultural productivity while preserving soil health and biodiversity. By taking advantage of the natural properties of these bacteria, we can help make agriculture more resilient in the face of today's environmental and climatic challenges.

3 Bacillus species as Plant Growth Promoting Bacteria (PGPB)

Bacillus species occupy a prominent place among plant growth-promoting bacteria (PGPB) thanks to their ability to enhance plant growth, yield, and resilience to a variety of environmental stresses. They constitute up to 95% of the Gram-positive bacterial populations in the soil and rhizosphere [26]. With the advantage of producing extracellular polysaccharides (EPS), some Bacillus species form a thin biofilm on the roots, enabling them to colonize roots and establish beneficial relationships with the plant, thus contributing to growth promotion. Numerous Bacillus spp. have been reported to have plant growth-promoting attributes, including B. subtilis, B. velezensis, B. azotofixans, B. macerans, B. circulans, and B. coagulans, among others. These beneficial microorganisms exert their plant growth-promoting potential through various mechanisms, mainly (3.1) nutrient solubilization, (3.2) phytohormone production, (3.3), bioactive compounds production, and (3.4) inducing systematic resistance (ISR).

3.1 Nutrient solubilization and nitrogen fixation

One of the key mechanisms by which Bacillus spp. promote plant growth is phosphate solubilization and atmospheric nitrogen fixation. By making phosphorus more available to plants, these bacteria improve nutrient utilization efficiency, an essential factor in plant growth. At the same time, certain Bacillus strains are capable of fixing atmospheric nitrogen, thus contributing to the supply of a fundamental plant nutrient, often limiting in agricultural systems [27].

3.2 Phytohormone production

Bacillus spp. can also produce phytohormones, such as auxins, gibberellins and cytokinins, which play a crucial role in regulating plant growth and development. Auxin production, for example, can stimulate root elongation, increasing the plant's surface area for absorption and enabling it to access more nutrients and water in the soil. This ability to modulate plant hormone production is particularly beneficial in conditions of stress, helping plants to maintain growth and productivity.

3.3 Bioactive compounds production

Bacillus spp. can produce a wide range of bioactive secondary metabolites (BSMs) that play crucial roles in the biocontrol of plant diseases. These metabolites include peptides, enzymes, polyketides, proteins, Volatile Organic Compounds (VOCs). The BSMs are involved in antagonism against microbial pathogens and in the induction of systemic resistance in plants [28]. They act as signals at sub-inhibitory concentrations and can also function as antimicrobials upon reaching threshold amounts, at least locally around plant tissues. Some of the key bioactive metabolites produced by Bacillus spp. include surfactin, volatiles such as acetoin and 2,3-butanediol, and compounds like 3-pentanol [29]. These metabolites are involved in inducing immune responses in plants, interacting with plant membrane lipids, and modulating the plant plasma membrane composition to trigger induced systemic resistance.

3.4 Inducing systematic resistance

Another important aspect of the action of Bacillus spp. as PGPBs is their ability to induce systemic resistance in host plants. This induced resistance helps plants defend themselves against a range of pathogens, including bacteria, viruses and fungi. Bacillus spp. can trigger a defense response in the plant, resulting in increased production of antimicrobial compounds and
fortification of cell walls, thereby reducing susceptibility to infection [30].

4 Role of *Bacillus* in drought mitigation

*Bacillus*, as soil bacteria, plays a crucial role in modulating plant response to drought conditions. Their ability to promote plant resilience to drought relies on several mechanisms, including the production of water-retaining substances and the enhancement of nutrient and water uptake by plants. These mechanisms help mitigate the negative effects of drought on crop growth and yield, offering promising avenues for the development of sustainable agricultural strategies in the face of climate challenges.

4.1 Production of water-absorbing substances

*Bacillus* are capable of producing and secreting exopolysaccharides (EPS), long-chain sugar polymers that play an important role in water retention in the rhizosphere, the soil zone surrounding plant roots. These hydrophilic substances form a matrix around the roots, increasing the soil's capacity to retain water. This property is particularly beneficial in times of drought, as it helps maintain adequate hydration around the roots, reducing the water stress suffered by plants. In addition, EPS can improve soil structure by promoting the aggregation of soil particles, which improves porosity and the soil's capacity to retain water, thus facilitating better access to water for plants [31, 32].

4.2 Improved nutrient and water uptake

Beyond their ability to retain water in the soil, *Bacillus* play a decisive role in improving nutrient and water uptake by plants, acting through a variety of synergistic mechanisms that support plant growth under conditions of water stress [33]. A crucial aspect of the beneficial action of *Bacillus* is their ability to solubilize key nutrients, such as phosphorus, which become less accessible to plants in periods of drought. Through biochemical processes, these bacteria transform phosphorus and other nutrients into forms that are more soluble and therefore more easily assimilated by plant roots. This transformation plays an essential role in plant nutrition, enabling optimal growth and development even when water resources are limited, thus ensuring sustained agricultural productivity [27]. In addition, some *Bacillus* has the ability to synthesize phytohormones, notably auxins, which stimulate the expansion and development of the root system. This stimulation promotes more extensive exploration of the soil by the roots, increasing their capacity to absorb available water and nutrients. As a result, plants benefit from better nutrition and hydration, which is particularly advantageous in arid environments or when there is a temporary drop in water availability [33]. Finally, *Bacillus* helps improve plant tolerance to water stress by inducing the expression of genes linked to stress resistance. This molecular interaction between bacteria and plants activates signalling pathways that enhance plants' ability to maintain normal physiological functioning under water stress. As a result, crops are less affected by periods of drought, resulting in better growth and higher yields, even under unfavourable environmental conditions. In short, *Bacillus* offers a natural and effective solution for supporting plant growth in water-stressed conditions, by acting on nutrient and water uptake. Their use in agricultural practices can therefore play a significant role in mitigating the effects of drought on crops, thus contributing to the resilience and sustainability of agricultural systems in the face of the challenges posed by climate change.

4.3 Case studies and relevant research findings

The importance of *Bacillus* in drought mitigation has been highlighted by a number of case studies and research studies, which demonstrate their ability to improve plant resilience under conditions of water stress. This research underlines not only the effectiveness of *Bacillus* as plant growth support agents, but also their potential in the development of sustainable agricultural strategies in the face of climatic challenges. A notable study was carried out on wheat crops, where seed inoculation with specific *Bacillus* strains resulted in a significant increase in plant growth and yield under water stress. Treated plants showed improved water use efficiency, increased biomass and improved photosynthesis compared to untreated controls. These results indicate that *Bacillus* can play a crucial role in modulating plant response to water shortage, enhancing their ability to maintain vital functions even under drought conditions [34]. In another study, tomato plants inoculated with *Bacillus* subtilis showed increased resistance to drought, with positive effects on root growth, chlorophyll content and fruit yield. *Bacillus* application promoted better water and nutrient uptake, contributing to increased productivity of tomato plants under water stress. These observations underline the potential of *Bacillus* to induce beneficial physiological and biochemical changes that enhance plant tolerance to drought [35].

Other relevant research explored the use of *Bacillus* in arid conditions, where legume crops inoculated with these bacteria showed significant improvements in growth, nitrogen fixation and drought resistance. This study highlights the role of *Bacillus* not only in promoting plant growth, but also in improving efficiency in the use of limited environmental resources, such as water and nutrients [36]. These case studies and research results clearly illustrate the potential of *Bacillus* as a biotechnological tool for mitigating the effects of drought on crops. By improving plant resilience to water stress, *Bacillus* offer a promising avenue for increasing agricultural productivity in water-stressed environments, thus contributing to food security and environmental sustainability in the context of climate change. Their use as a soil bio-amendment or as an integral part of integrated crop management represents an ecologically sound and economically viable strategy for meeting the challenges of modern agriculture.
5 Role of *Bacillus* in plant disease management

*Bacillus* species have emerged as key players in the field of agricultural research, providing an eco-friendly and sustainable option to traditional chemical pesticides for managing plant diseases. Their protective role involves a diverse array of mechanisms, including direct antagonism against pathogens and beneficial alterations to the plant's physiological state. Studies have shown the efficacy of *Bacillus* in defending against numerous plant diseases, such as the successful use of *Bacillus subtilis* against gray mold in strawberries and tomatoes, and *Bacillus thuringiensis* as a biopesticide targeting various insect larvae. These achievements underscore *Bacillus*'s value in integrated pest management strategies, contributing to reduced chemical use and fostering sustainable farming practices. Ultimately, *Bacillus*'s dual approach to disease prevention, through direct action and plant health enhancement, represents an innovative, green solution for improving crop yields and protecting ecosystems within the framework of sustainable agricultural development [37].

5.1 Pathogen suppressing

*Bacillus* species can produce a broad array of secondary metabolites that directly suppress plant pathogens. These include antibiotics lytic enzymes, volatile compounds, and endotoxins. For example, Antibiotics produced by *Bacillus*, such as bacitracin, polymyxin and surfactin, have a broad spectrum of action against many pathogenic microorganisms, including bacteria, fungi and even some viruses. In addition, lytic enzymes such as chitinases and glucanases break down the cell walls of fungal pathogens, limiting their ability to infect plants [38]. For instance, chitinase produced by *B. pumilus* CCIBP-C5, and *B. cereus* CRS7 has been shown to decrease the growth of *Rhizoctonia solani* [39], and *B. cinerea* respectively [29]. Volatile compounds emitted by *Bacillus* species can also interfere with the growth and development of phytopathogens by inhibiting their germination, growth, and reproduction. Furthermore, δ-endotoxins produced mainly by *Bacillus thuringiensis* (Bt), exhibit insecticidal properties, targeting intestinal membrane of insect target that may act as vectors for plant pathogens.

5.2 Competition for resources and space

Another aspect of *Bacillus*' protective role against plant diseases is their ability to compete with pathogens for resources and space. By effectively colonizing the rhizosphere and plant tissues, *Bacillus* can limit the space available for pathogen establishment and reduce their access to essential nutrients. This competition can significantly weaken pathogens and reduce their virulence, thus contributing to the overall health of the plant [40].

5.3 Induction of systemic acquired resistance in plants

In addition to their direct antimicrobial action, *Bacillus* can induce systemic acquired resistance (SAR) in host plants. This mechanism involves the stimulation of the plant's immune system, preparing it to better resist future pathogen attacks. The induction of ASR by *Bacillus* is often mediated by the production of signaling compounds that activate the plant's defense pathways. This form of "vaccine" protection is particularly valuable, as it enables the plant to respond more quickly and effectively to infections, thereby reducing the damage caused by disease [41].

5.4 Reshaping plant microbiome

Recent studies highlight the crucial role of plant-associated microbiomes, often considered a plant's "second genome," in maintaining health and disease suppression. *Bacillus* species, for example, have been shown to influence the soil's microbial community, promoting beneficial microorganisms that directly combat pathogens. Notably, inoculation with specific *Bacillus* strains has led to increased presence of beneficial microbes like *Pseudomonas* spp., which have shown effective disease resistance, such as against banana wilt and tomato bacterial wilt. These interactions, including metabolic exchanges between *Bacillus* and *Pseudomonas*, enhance biofilm formation and pathogen inhibition. Additionally, applications of *Bacillus* biocontrol agents have been demonstrated to alter soil microbiomes, enriching antifungal microbial groups and supporting plant health. This biocontrol strategy extends beyond the rhizosphere to the phyllosphere, where *Bacillus velezensis* treatments have reshaped microbial communities to suppress foliar diseases. These insights into biocontrol mechanisms offer new strategies for disease management by modulating microbial communities in plant environments.

6 Agricultural applications of *Bacillus* spp.

Thanks to their wide range of beneficial properties, *Bacillus* spp. have found their way into a variety of agricultural applications, offering sustainable solutions to increase crop productivity while reducing agriculture's environmental impact. These applications take advantage of *Bacillus*’ unique capabilities to promote plant growth, improve resilience to stress and combat disease (Figure 1).

6.1 Biofertilizers

The use of *Bacillus* as biofertilizers is one of the most promising applications in agriculture. These microorganisms improve the availability of nutrients to plants, notably by solubilizing phosphorus and fixing atmospheric nitrogen, two key elements in plant
nutrition. By promoting better nutrient uptake, *Bacillus*-based biofertilizers contribute to healthy, vigorous plant growth, resulting in higher crop yields. What's more, by reducing dependence on chemical fertilizers, these biofertilizers play a crucial role in preserving soil health and reducing environmental pollution [42].

6.2 Biocontrol agents

As biocontrol agents, *Bacillus* contributes to plant disease management by inhibiting pathogen growth through the production of antibiotics and lytic enzymes, and by inducing plant resistance. This approach to biological disease control reduces the need for chemical fungicides and bactericides, contributing to healthier, more sustainable agriculture. In addition, the use of *Bacillus* in biocontrol promotes microbial biodiversity in the soil, an essential element in maintaining the health and fertility of agricultural ecosystems [43]. *Bacillus* are also used as biopesticides to protect crops against a variety of pathogens and pests. For example, *Bacillus thuringiensis* produces toxins that are specifically toxic to certain insect pests, offering a targeted biological control method that minimizes damage to plants and the ecosystem. Unlike chemical pesticides, *Bacillus*-based biopesticides have the advantage of not generating resistance in pests, and of not leaving harmful residues on agricultural produce or in the environment [44].

6.3 Phytostimulant agents

*Bacillus*-based phytostimulants are among the commercially available biostimulants. *Bacillus* species can act as phytostimulators by producing phytohormones such as gibberellic acid (GA) and indole-3-acetic acid (IAA), which directly influence plant development, including seed germination, stem elongation, and the development of roots and shoots. They play a specific role as phytostimulants in sustainable agriculture by promoting plant growth through various mechanisms.

6.4 Bioremediation agents

The unique properties and capabilities of *Bacillus spp.* make them valuable agents in the bioremediation of soil pollutants, contributing to the sustainable management of environmental contamination. Some *Bacillus spp.* strains have the capability to reduce various pollutants in the environment, including heavy metals such as lead, cadmium, mercury, chromium, arsenic, and nickel [45]. These bacteria can employ strategies such as biosorption, extracellular polymeric substance (EPS)-mediated biosorption, bioaccumulation, and bioprecipitation to reduce the amounts of these metals in the environment.

Fig. 1. Potential applications of *Bacillus* species in agriculture.

7 Challenges and future perspectives

7.1 Key Challenges

Interactions between plants and microbes are characterized by a high degree of specificity, where a microbial strain that benefits one plant species may not offer the same benefits, or even be inoperable, for another. This specificity can be attributed to a number of factors, including the specific molecular recognition mechanisms between the host plant and the microbe, as well as the particular nutritional and growth requirements of each plant species.

This specificity suggests the need for detailed studies to identify the *Bacillus* strains most beneficial to specific plant species. This involves precise characterization of the molecular and physiological interactions between *Bacillus* and their plant hosts, in order to select strains that optimize growth, stress resilience and disease resistance for particular crops. The research approach must therefore be highly personalized, taking into account the unique characteristics of each plant-microbe association.

Interactions between PGPBs and plants are strongly impacted by environmental conditions, such as pH, temperature, salinity and microbiome biodiversity. These environmental factors can significantly modify the efficacy of PGPBs by influencing their survival, root colonization and ability to perform beneficial functions for plants. For example, variations in temperature can affect the production of phytohormones by *Bacillus*, while changes in soil salinity can influence their ability to solubilize phosphates or fix nitrogen. Similarly, soil pH can alter the availability of nutrients solubilized by *Bacillus*, affecting their usefulness to the plant. In addition, the biodiversity of the soil microbiome plays a crucial role in determining the outcome of interactions between PGPBs and plants, as it can facilitate or hinder *Bacillus* efficacy through competitive or synergistic mechanisms.

These complex interactions suggest that the application of *Bacillus* as a PGPB requires a thorough understanding of the soil ecosystem and environmental conditions specific to each agricultural site. Future research should focus on developing flexible, adaptive application strategies capable of maximizing the benefits of *Bacillus* under a diverse range of
environmental conditions. This could include the development of Bacillus formulations specific to given environments, or the combination of strains to create microbial consortia capable of operating effectively under diverse conditions.

In summary, the successful use of Bacillus in agriculture relies on a detailed understanding of the specificity of plant-microbe interactions and the influence of environmental conditions on these interactions. A research and application approach incorporating this knowledge is essential to fully exploit the potential of Bacillus as a PGPB, thus promoting sustainable and resilient agriculture.

7.2 Future Perspectives

The development of innovative formulations is essential to facilitate the application of Bacillus and improve their efficacy in various agricultural contexts. This includes the creation of products adapted to specific modes of application, such as foliar spraying, seed inoculation, or soil application. The aim is to develop formulations that maximize Bacillus survival and colonization, while being easy for farmers to use. At the same time, it is crucial to expand marketing efforts to raise awareness of these organic technologies and promote their adoption into standard farming practices.

Future research must also focus on understanding and improving the viability of Bacillus once applied in the field. This involves studying how environmental conditions, such as climate, soil type and the presence of other micro-organisms, affect the survival and efficacy of Bacillus. The aim is to identify the key factors influencing Bacillus performance under field conditions, and to develop strategies for optimizing their viability and functioning in a variety of agricultural systems.

Increasing the shelf-life and stability of Bacillus-based products is a priority to guarantee their long-term efficacy and facilitate their storage and distribution. This can be achieved by developing microencapsulation techniques, stabilizing formulations with stress protectors, or freeze-drying. These approaches can help preserve the viability of Bacillus and maintain their biological activity until they are used.

Exploiting genetic engineering to improve Bacillus characteristics offers exciting prospects. For example, genetic manipulation could be used to increase the production of substances beneficial to plants, improve Bacillus resistance to adverse environmental conditions, or enhance their ability to form spores. Spore formation is of particular interest, as it confers on Bacillus an exceptional resistance to environmental stresses, which may be crucial to their survival and functioning in field conditions.

Future prospects for the use of Bacillus are vast and varied, covering improved formulations, expanded commercialization, increased field viability, extended shelf life and stability, and the exploitation of advances in genetic engineering. By pursuing these lines of research and development, it is possible to optimize the use of Bacillus to support productive and sustainable agriculture.

Conclusion

Bacillus species have emerged as key players in bolstering plant defense mechanisms, proving to be invaluable in the enhancement of drought resilience and the management of plant diseases. The myriad of strategies employed by these bacteria—ranging from the production of antioxidants that mitigate oxidative stress in plants to the intricate regulation of plant hormones—highlights the multifaceted role they play in strengthening plant responses to environmental challenges and disease pressures.

The ability of Bacillus spp. to induce systemic resistance, improve nutrient uptake, and modulate stress responses provides a biological toolkit that can be tapped into for developing more sustainable agricultural practices. By exploiting the adaptive and protective benefits conferred by Bacillus strains, researchers and agronomists can work toward creating agricultural systems that are not only more productive but also inherently equipped to cope with the changing climate and the associated biotic and abiotic stresses. In this context, the strategic application of Bacillus spp. in agricultural settings is not just a scientific endeavor but a necessary shift towards ensuring food security and ecosystem health in an era marked by rapid environmental changes.

References

5. A. Sharma and V. Sahni, Climate Change and River Waters in South Asia: Scarcity, Security and the Avoidance of Zero-Sum Approaches in the Anthropocene Epoch (Routledge India, 2024).
8. P. R. Nair, B. M. Kumar, V. D. Nair, P. R. Nair, B. M. Kumar, and V. D. Nair, Soil Conservation and Control of Land-Degradation (2021). https://doi.org/10.1007/978-3-030-75358-0_18


