Review

The impact of climate change on plant growth-promoting rhizobacteria (PGPR): Implications for sustainable agriculture

Ali Raza [1,2,†], Jueping Song [1,2,†], Miaomiao Huang [1,2], Qian Li [1,2], Sara Janiad [3], Shuang Liu[1,2], Muhammad Ahmad Hassan [4*]

[1]Anhui Province Key Laboratory of Crop Integrated Pest Management, School of Plant Protection, Anhui Agricultural University, Hefei, 230036, China

[2]Anhui Provincial Key Laboratory of Microbial Pest Control, Anhui Agricultural University, Hefei, 230036, China

[3]Department of Microbiology & Molecular Genetics, The Women University of Multan, Multan 6000, Pakistan

[4]College of Resource and Environment, Anhui Agricultural University, Hefei, 230036, China

† These authors have contributed equally to this work.

Corresponding author: M. Ahmad Hassan(ahmaduaf93@ahau.edu.cn).

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Abstract

Important challenges to agriculture are posed by climate change because it affects plant growth, soil health. Plant Growth Promoting rhizobacteria (PGPR) are central to sustainable agriculture in terms of improving nutrient uptake, increasing stress susceptibility and improving soil fertility. The effect of rising temperatures, changes in precipitation, and increased concentration of CO_2 on PGPR diversity, functionality and plant microbe interactions is reviewed. It emphasizes the need for of adaptive procedures including engineering stress tolerant PGPR strains, biofertilizer application optimization and integrated pest management. Solving these problems will enhance crop productivity, soil quality, as well as ecosystem resilience and will contribute to food security and sustainable farming in changing climatic context.

Keywords: Climate Change; Plant Growth-Promoting Rhizobacteria (PGPR); Sustainable Agriculture; Soil Health

Introduction

The detrimental effects of climate change on the soil quality in the agricultural industry have gained global recognition in recent years. Certain stressors caused by climate change, such as salt, drought, and temperature swings, severely impair physiological reactions, productivity, and total output of crops. This poses a major risk to agroecosystems and global food security (Javeed et al. 2023). Climate change is decreasing crop output and increasing the cost of agricultural goods, putting 77 million more people in jeopardy of food poverty by 2050. Significant increases in global temperature, together with the emergence of additional abiotic stressors, have a negative impact on crop yield.

In this scenario, eco-friendly technologies and sustainable farming methods can help break the cycle by boosting yields under various more challenging circumstances and improving resource utilization of resources (Pareek et al., 2020). The goal is to sustain the health of the soil by sequestering soil carbon, maintaining soil organic matter and mineral content, enhancing soil organic matter and mineral content, and enhancing healthy crop yields while decreasing detrimental inputs, thus regulating extreme climatic conditions. Certain plants have developed flexibility to tolerate these fluctuations, so they may grow very well in harsh growing environments. However, most agricultural plants will become less productive because of the harsher environmental stresses that will outpace their ability to adapt.

Bacteria found in the rhizosphere of plants belong to a variety of species and are known as rhizobacteria. Among the majority of rhizobacteria, a few species are known to promote plant development and are referred to as "beneficial rhizobacteria." Beneficial rhizobacteria have several advantages in terms of cost, environmental effects, and soil fertility and should be considered as a sustainable alternative to current techniques. However, the keystone of green agriculture microbiology is the sustained use of these advantageous and promising rhizobacteria (Oleńska et al., 2020).

Plants endowed with plant growth promoting rhizobacteria (PGPR) exhibit enhanced root hair formation and a more efficient uptake of minerals and microelements from the soil. Numerous plant species benefit from PGPR treatment, including rice (*Oryza sativa*), lentils (*Lens esculenta*), cucumbers (*Cucumis sativus*), soybeans (*Glycine max*), and peas (*Pisum sativum*). PGPR also confer fundamental resilience to various abiotic stresses in plants, such as heavy metals, drought, and salinity, by modulating plant physiology. The symbiotic relationship between leguminous plants and microorganisms, facilitated by bio-mineralization and symbiotic co-development, holds significant potential for enhancing soil quality and fertility.

Various types of plant growth-promoting rhizobacteria (PGPR) in soil stifle many plant pathogens and endorse plant development through various strategies, for example, direct and indirect mechanisms for the generation of various phytohormones (Cassán et al., 2014), mineralization (Yazdani et al., 2009) and disintegration of organic matter, and increase the bioavailability of various mineral supplements, such as iron and phosphorous (Orhan et al., 2006; Bhattacharyya and Jha, 2012). PGPR occupy the rhizosphere with *Azotobacter* (Gurikar et al., 2016), *Bacillus* (Sivasakthi et al., 2014), Achromobacter (Vyas et al., 2018), Pantoea (Mishra et al., 2011), *Microbacterium* (Shrivastava and Kumar, 2013), *Enterobacter* (Jha et al., 2011), Paenibacillus (Yang et al., 2009), *Serratia* (Koo and Cho, 2009), *Klebsiella* (Habibi et al., 2014), *Burkholderia* (Nailwal et al., 2014), *Pseudomonas* (Fernando et al., 2005), and *Streptomyces* (Harikrishnan et al., 2014) and so forth. PGPR are commonly utilized as inoculates for biofertilization, biocontrol, and biostimulation (Prashar et al., 2014). These microorganisms, along with different organisms, improve plant development under various ecological stress conditions (Barea et al., 2002). PGPR are a contemptible and effectively accessible source for alleviating various biotic and abiotic stresses (Barriuso et al., 2008). PGPR generally improve plant development endorsement by activating plant development hormones (Le Mire et al., 2016), antioxidant frameworks (Jha and Subramanian, 2018), siderophore production (Kloepper et al., 1980) and upgrading the nutritional competency of the plants (Prasad et al., 2015).

Plant growth-boosting rhizobacteria are essential components of sustainable agriculture because they enhance plant development and improve soil health through multiple processes. However, the changing environment poses a substantial threat to these microbes. This review aims to examine the influence of climate change on (PGPR) and emphasize its effects on their diversity, functionality, and plant-microbe interaction. By understanding these effects, strategies can be developed to reduce the harmful impacts of climate change and improve the resilience of agricultural systems.

Change Impacts on PGPR Rising Temperatures

A significant rise in temperature induced by climate change can significantly affect the functionality and diversity of PGPR. Elevated temperatures can accelerate the metabolism of microorganisms and enhance the activities of some PGPR; however, extreme heat can lead to thermal stress, which can reduce the viability and enzymatic activity of these bacteria. For instance, the nitrogen-fixing efficiency of rhizobium species decreases at raised temperatures, impacting legume crops, such as soybeans and chickpeas. Notably, Rhizobium leguminosarum, which forms a symbiotic association with these legumes, experiences a significant reduction in nitrogenous activity due to increased temperature, specifically approximately 30°C, which later decreases nitrogen availability for these crops (Biljon and Sifi, 2021). Similarly, *Bradyrhizobium japonicum*, which is essential for soybean cultivation, shows a remarkable reduction in nodule formation and nitrogenous activities when the exporter has a temperature of approximately 35 cm, which results in reduced soybean yield (Hungria and Franco, 1993; EL Sabagh et al., 2020). Raised temperature above 30°C negatively affects *Sinorhizobium meliloti* of bacteria associated with alfa alfa. The bacterium has impaired nodule formation. As a result, diminished nitrogen fixation rate negatively affects plant growth (Aranjuelo et al., 2014). *Mesorhizobium ciceri*, is associated with chickpeas and exhibits a significant decline in nitrogenous activity above 32°C, which severely affects chickpea growth and yield due to reduced survival of the bacteria in the soil (Graham, 1992; Zhang et al., 2020). Additionally, *Rhizobium etli*, known for its linkage with the common bean, reduces its nitrogen-fixing ability at temperatures above 30°C. This leads to lower bean yield and compromised plant health (Alexandre et al., 2014; Hidalgo-García et al., 2023). These examples show the vulnerability of Rhizobium species to increasing temperatures. This emphasizes the need to develop heat-tolerant strains and adopt agronomic practices to mitigate the thermal stresses caused by climate change on crops and PGPRs.

Altered Precipitation Patterns

Altered precipitation patterns lead to more frequent flooding and droughts, thereby posing challenges to the PGPR. These water stresses can enable PGPR colonization in the roots of plants, and hence decrease their ability to produce growth-promoting substances. For example, drought stress reduces the ability of *Azospirillum brasilense* to promote wheat (Bashan and De-Bashan, 2010). Similarly, plant growth, pathogen suppression, and Pseudomonas fluorescence exhibit diminished activity under water-stressed conditions due to reduced soil moisture (Mayak et al., 2004; Khan et al., 2020). Conversely, excessive rain and flooding can cause anaerobic conditions for aerobic PGPR, such as Bacillus subtilis, used in crop protection (in tomato protection against soil-borne diseases) (Vivas et al., 2003).

Barnard et al., (2015) Astorga-Eló et al., (2021). Flooding can also lead to the depletion of oxygen in the soil and deprive beneficial microbes of survival, affecting their ability to support plant growth under these stresses (Hattori et al., 2013; Shen et al., 2021). These altered precipitation patterns underscore the pressing need for selecting and Engineering the PGPR strange for environmental stresses that can withstand this adverse climatic change to support sustainable agriculture practices.

Increased CO_2 Levels

Increased carbon dioxide levels in the atmosphere can alter the physiology of plants and root exudation patterns, impacting PGPR (Panchal et al., 2022). The elevated carbon dioxide levels can enhance root biomass and exudation, potentially providing more substrates for these PGPRs. However, the quality and composition of root exudates may change, affecting the type of PGPR that can be driven. For example, increased carbon dioxide levels have been shown to alter the root exudate profile of rice, which affects the colonization efficiency of *P. fluorescence* (Phillips et al., 2011). Additionally, studies have shown that elevated carbon dioxide levels can affect the rhizosphere microbial community by modifying the exudation of amino and organic acids in wheat roots (Griffiths et al., 1998; Grover et al., 2015). Altered carbon dioxide levels can either promote or inhibit the growth of specific PGPR, defending against metabolic capabilities and adaptabilities to altered root exudate composition (Hu et al., 1999).

Impact on Plant-PGPR Interactions

The signaling and symbiotic relationships between plants and PGPR can be disrupted by climate change. tress conditions such as drought and elevated carbon dioxide level, heat precipitation patterns can modify the plant root profiles and affect the recruitment as well as activity of PGPR changes in the road architecture, and exhibition patterns can impact the functionality and spatial distribution of PGPR in the rhizosphere, thereby potentially reducing their plant growth-promoting abilities (Ullah et al., 2021).

Changes in Symbiosis

Complex signaling pathways and mutualistic interactions are key factors in the symbiotic relationship between plants and PGPR. Climate-induced stress can disturb these interactions and lead to a breakdown of this symbiotic relationship (Surówka et al., 2020). Plants under temperature stress have trouble producing the signals required for PGPR and plant communication. For example, peas and beans do not start their symbiosis with rhizobia due to disruption of important lipochitooligosaccharides (LCO) or node factors by rhizobia (Alexandre and Oliveira, 2013; Ullah et al., 2021). Climate change hurts methods that allow plants and helpful microbes to communicate normally in new environments (Askari-Khorsgani et al., 2018; Neill et al., 2019).

Consequences for Plant Growth and Soil Health

The climatic consequences of PGPR can have a detrimental effect on plant growth development and productivity, and reduced PGPR activity can lead to decreased nutrient availability and nutrient uptake. It can cause stunted growth and reduce crop yield. For instance, reduced nitrogen fixation by Rhizobium species can significantly affect crops such as soya beans and peas. The disruption of PGPR PGPR-mediated biocontrol mechanism can 's vulnerability to pathogens as well as increase the plant's vulnerability to pathogens (Khan and Mehmood, 2023; Lagunas et al., 2023).

Effects on Soil Health

Climate change can also affect soil health by influencing PGPR and broader microbial communities (Veni et al., 2020). Changes in the microbial community and diversity can alter the functionality of these microbes, thereby altering nutrient cycling processes. These altered processes can also affect the soil fertility and structure. For example, reduced phosphate solubilization by *Pseudomonas fluorescence* can lead to lower soil phosphate levels. Hence, it can affect crop phosphate solubilization by *P. fluorescence*, leading to lower phosphate levels in the soil; hence, it can affect crops such as beans and rice. Furthermore, altered microbial dynamics in the soil can influence the organic matter composition of the soil and carbon sequestration, affecting the overall soil health and ecosystem overall (Zhang et al., 2020b; Dasila et al., 2023).

Mitigating Strategies

Growing tough plant varieties can help reduce the way climate change harms the Earth. Our goal is to develop plants that can stay healthy through both normal threats to their growth (biotic stress) and unusual events (abiotic stress). We also wanted to ensure that crops grew well around the beneficial soil bacteria. Our breeding plans must combine genetic engineering to make plants tougher and allow them to live well in challenging settings.

The PGPR requires soil moisture at the right level to perform its job. To protect PGPR from climate change, farmers must control the amount of water in the soil. Soil health will improve when we are smart about farming - keeping away from practices that damage soil without making changes that help maintain moisture and organic matter in the soil. Intercropping and using mulch and cover crops helps our soil to keep water and stay at the right temperature for PGPR to work well. Russian irrigation technology helps us use water well and loses less, ensuring that our soil remains moist enough for good PGPR work.

Biofertilizer methods help reduce the impact of climate change on plants and soil. PGPR bio-fertilizers are specialized bacteria that build soil fertility, help plants grow stronger, and keep the soil healthy and intact. We can create fertilizer supplies by growing PGPR that can resist drought through special breeding. Bio-fertilizers help plants grow better in times of water shortages. Using biofertilizer with PGPR gives plants better growth, helping PGPR to perform more effectively.

With Integrated Pest Management (IPM), we can reduce how climate change affects PGPR. Using fewer chemicals to grow plants while building up PGPR numbers can keep the soil in good shape and support life. These chemicals and pesticides hit the PGPR population directly because they were created to control them. Biological control methods work well with regular IPM programs to help farmers deal with climate change in a more sustainable manner.

Conclusion & Future Directions

The urgent need for sustainable agricultural methods is the focus of the current studies on the impact of climate change on plant growth promoting rhizobacteria (PGPR). However, the presence of these bacteria is essential for the growth and development of plants, as they improve the availability of nutrients and give the plant the ability to withstand stress.

However, climate change directly affects the population and potential activity of PGPR, which changes the interaction between the PGPR population and ecosystem services. Future research should focus on developing climate-specific agricultural techniques. An assessment of how changing surroundings affect PGPR and the intricate interplay between PGPR and soil health should be the focus of these studies. We also sought to examine the proliferation of new PGPR species and their future ability to be utilized under climate change conditions.

We urgently need to fill these knowledge gaps to develop strategies that mitigate the impact of climate change on PG PR, thereby promoting sustainable agriculture in society. These strategies will further increase plant productivity, soil health, and ecosystem resilience, and contribute to food security and environmental sustainability amid climate change. The global effort to compare climate change and promote more sustainable food security around the globe also requires support for precision agriculture practices that use PGPR.

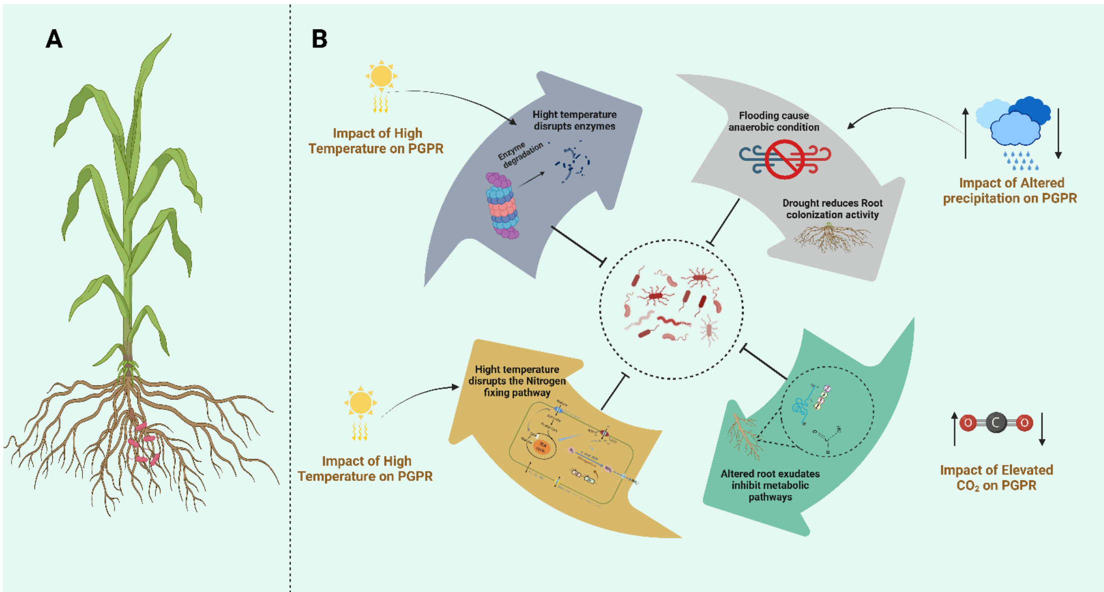

Figure 1 | **(A)** Plant with PGPR under normal Climate conditions**. (B)** Impact of Climate change on PGPR. The diagram illustrates how climate change impacts Plant Growth-Promoting Rhizobacteria (PGPR): rising temperatures reduce microbial viability, enzymatic activity, and nitrogen fixation (e.g., *Rhizobium* spp.); altered precipitation disrupts root colonization during drought and harms aerobic PGPR (e.g., *Bacillus* spp.) during flooding; increased CO_2 levels alter root exudates and microbial composition, reducing colonization efficiency (e.g., *Pseudomonas* spp.); and disrupted plant-PGPR interactions impair signaling, nutrient availability, and resilience.

Declarations

Ethics approval
Not applicable.

Consent to participate
Not applicable.

Consent for publication
Not applicable

Conflict of interest
Author declares no conflict of interest.

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Data availability
All the data generated are available in the manuscript.

Authors contribution
B.I. conceived the study, collected the data and wrote the original manuscript, and revised the manuscript.

References

1. Alexandre, A., Laranjo, M., Oliveira, S. (2014). Global transcriptional response to heat shock of the legume symbiont *Mesorhizobium loti* MAFF303099 comprises extensive gene downregulation. *DNA Research*, 21(2), 195-206.
2. Aranjuelo, I., Arrese-Igor, C., Molero, G. (2014). Nodule

performance within a changing environmental context. *Journal of Plant Physiology*, 171(12), 1076-1090.
3. Askari-Khorsgani, O., Flores, F., Pessarakli, M. (2018). Plant signaling pathways involved in stomatal movement under drought stress conditions. *Advances in Plant and Agricultural Research*, 8(3), 290-297.
4. Astorga-Eló, M., Gonzalez, S., Acuña, J.J., Sadowsky, M.J., Jorquera, M.A. (2021). Rhizobacteria from 'flowering desert' events contribute to the mitigation of water scarcity stress during tomato seedling germination and growth. *Scientific Reports*, 11(1), 13745.
5. Barea, J., Azcón-Aguilar, C., Azcón, R. (2002). Interactions between mycorrhizal fungi and rhizosphere micro-organisms within the context of sustainable soil-plant systems. *Multitrophic Interactions in Terrestrial Systems*, 65-68.
6. Barnard, R.L., Osborne, C.A., Firestone, M.K. (2015). Changing precipitation pattern alters soil microbial community response to wet-up under a Mediterranean-type climate. *The ISME Journal*, 9(4), 946-957.
7. Barriuso, J., Solano, B.R., Lucas, J.A., Lobo, A.P., García-Villaraco, A., Mañero, F.J.G. (2008). Ecology, genetic diversity and screening strategies of plant growth-promoting rhizobacteria (PGPR). *Journal of Plant Nutrition*, 1-17.
8. Bashan, Y., De-Bashan, L.E. (2010). How the plant growth-promoting bacterium *Azospirillum* promotes plant growth—a critical assessment. *Advances in Agronomy*, 108, 77-136.
9. Bhattacharyya, P.N., Jha, D.K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. *World Journal of Microbiology and Biotechnology*, 28(4), 1327-1350.
10. Biljon, A.H., Sifi, B. (2021). Legume-rhizobia symbiosis under abiotic constraints: Performance system. *Agrociencia*, 55, 37-61.
11. Cassán, F., Vanderleyden, J., Spaepen, S. (2014). Physiological and agronomical aspects of phytohormone production by model plant-growth-promoting rhizobacteria (PGPR) belonging to the genus *Azospirillum*. *Journal of Plant Growth Regulation*, 33(2), 440-459.
12. Dai, Z., Pi, Q., Liu, Y., Hu, L., Li, B., et al. (2024). Response to temperature stress in rhizobia. *Critical Reviews in Microbiology*, 39(3), 219-228.
13. Dasila, H., Sah, V., Jaggi, V., Kumar, A., Tewari, L., Taj, G., Chaturvedi, S., Perveen, K., Bukhari, N.A., Siang, T.C. (2023). Cold-tolerant phosphate-solubilizing *Pseudomonas* strains promote wheat growth and yield by improving soil phosphorus (P) nutrition status. *Frontiers in Microbiology*, 14, 1135693.
14. El Sabagh, A., Hossain, A., Islam, M.S., Fahad, S., Ratnasekera, D., Meena, R.S., Wasaya, A., Yasir, T.A., Ikram, M., Mubeen, M. (2020). Nitrogen fixation of legumes under the family Fabaceae: adverse effect of abiotic stresses and mitigation strategies. *The Plant Family Fabaceae: Biology and Physiological Responses to Environmental Stresses*, 75-111.
15. Fernando, W.D., Nakkeeran, S., Zhang, Y. (2005). Biosynthesis of antibiotics by PGPR and its relation in biocontrol of plant diseases. *PGPR: Biocontrol and Biofertilization*, Springer, 67-109.
16. Graham, P.H. (1992). Stress tolerance in *Rhizobium* and *Bradyrhizobium*, and nodulation under adverse soil conditions. *Canadian Journal of Microbiology*, 38(6), 475-484.
17. Griffiths, B., Ritz, K., Ebblewhite, N., Paterson, E., Killham, K. (1998). Ryegrass rhizosphere microbial community structure under elevated carbon dioxide concentrations, with observations on wheat rhizosphere. *Soil Biology and Biochemistry*, 30(3), 315-321.
18. Grover, M., Maheswari, M., Desai, S., Gopinath, K., Venkateswarlu, B. (2015). Elevated CO2: Plant associated microorganisms and carbon sequestration. *Applied Soil Ecology*, 95, 73-85.
19. Gurikar, C., Naik, M., Sreenivasa, M. (2016). Azotobacter: PGPR activities with special reference to effect of pesticides and biodegradation. *Microbial Inoculants in Sustainable Agricultural Productivity*, Springer, 229-244.
20. Habibi, S., Djedidi, S., Prongjunthuek, K., Mortuza, M.F., Ohkama-Ohtsu, N., Sekimoto, H., Yokoyoma, T. (2014). Physiological and genetic characterization of rice nitrogen fixer PGPR isolated from rhizosphere soils of different crops. *Plant and Soil*, 379(1-2), 51-66.
21. Harikrishnan, H., Shanmugaiah, V., Balasubramanian, N. (2014). Optimization for production of Indole acetic acid (IAA) by plant growth promoting *Streptomyces* sp. VSMGT1014 isolated from rice rhizosphere. *International Journal of Current Microbiology and Applied Sciences*, 3(8), 158-171.
22. Hattori, R., Matsumura, A., Yamawaki, K., Tarui, A., Daimon, H. (2013). Effects of flooding on arbuscular mycorrhizal colonization and root-nodule formation in different roots of soybeans. *Agricultural Sciences*, 2013.
23. Hidalgo-García, A., Tortosa, G., Pacheco, P.J., Gates, A.J., Richardson, D.J., Bedmar, E.J., Girard, L., Torres, M.J., Delgado, M.J. (2023). *Rhizobium etli* is able to emit nitrous oxide by connecting assimilatory nitrate reduction with nitrite respiration in the bacteroids of common bean nodules. *Journal of Plant Interactions*, 18(1), 2251511.
24. Hu, S., Firestone, M.K., Chapin, F.S. (1999). Soil microbial feedbacks to atmospheric CO2 enrichment. *Trends in Ecology & Evolution*, 14(11), 433-437.
25. Hungria, M., Franco, A.A. (1993). Effects of high temperature on nodulation and nitrogen fixation by *Phaseolus vulgaris* L. *Plant and Soil*, 149, 95-102.
26. Javeed, H.M.R., Ali, M., Qamar, R., Sarwar, M.A., Jabeen, R., Ihsan, M.Z., Zamir, M.S.I., Shahzad, M., Khalid, S., Saeed, M.F. (2023). Food Security Issues in Changing Climate. *Climate Change Impacts on Agriculture: Concepts, Issues and Policies for Developing Countries*, Springer, 89-104.
27. Jha, C.K., Aeron, A., Patel, B.V., Maheshwari, D.K., Saraf, M. (2011). Enterobacter: role in plant growth promotion. *Bacteria in Agrobiology: Plant Growth Responses*, Springer, 159-182.
28. Jha, Y., Subramanian, R. (2018). From interaction to gene induction: An eco-friendly mechanism of PGPR-mediated stress management in the plant. *Plant Microbiome: Stress Response*, Springer, 217-232.
29. Khan, N., Mehmood, A. (2023). Revisiting climate change impacts on plant growth and its mitigation with plant growth-promoting rhizobacteria. *South African Journal of Botany*, 160, 586-601.
30. Khan, N., Ali, S., Tariq, H., Latif, S., Yasmin, H., Mehmood, A., Shahid, M.A. (2020). Water conservation and plant survival strategies of rhizobacteria under drought stress. *Agronomy*, 10(11), 1683.
31. Kloepper, J.W., Leong, J., Teintze, M., Schroth, M.N. (1980). Enhanced plant growth by siderophores produced by plant growth-promoting rhizobacteria. *Nature*, 286(5776), 885.
32. Koo, S-Y., Cho, K-S. (2009). Isolation and characterization of a plant growth-promoting rhizobacterium, *Serratia* sp. SY5. *Journal of Microbiology and Biotechnology*, 19(11), 1431-1438.
33. Lagunas, B., Richards, L., Sergaki, C., Burgess, J., Pardal, A.J., Hussain, R.M., Richmond, B.L., Baxter, L., Roy, P., Pakidi, A. (2023). Rhizobial nitrogen fixation efficiency shapes endosphere bacterial communities and *Medicago truncatula* host growth. *Microbiome*, 11(1), 146.
34. Le Mire, G., Nguyen, M., Fassotte, B., du Jardin, P., Verheggen, F., Delaplace, P., Jijakli, H. (2016). Implementing biostimulants and biocontrol strategies in the agroecological management of cultivated ecosystems. *Biotechnologie, Agronomie, Société et Environnement*.
35. Mayak, S., Tirosh, T., Glick, B.R. (2004). Plant growth-promoting bacteria confer resistance in tomato plants to salt

stress. *Plant Physiology and Biochemistry*, 42(6), 565-572.

36. Mishra, A., Chauhan, P.S., Chaudhry, V., Tripathi, M., Nautiyal, C.S. (2011). Rhizosphere competent *Pantoea agglomerans* enhances maize (*Zea mays*) and chickpea (*Cicer arietinum* L.) growth, without altering the rhizosphere functional diversity. *Antonie Van Leeuwenhoek*, 100(3), 405-413.
37. Nailwal, S., Anwar, M.S., Budhani, K.K., Verma, A., Nailwal, T.K. (2014). *Burkholderia* sp. from rhizosphere of *Rhododendron arboretum*: isolation, identification and plant growth promotory (PGP) activities. *Journal of Applied and Natural Science*, 6(2), 473-479.
38. Neill, E.M., Byrd, M.C., Billman, T., Brandizzi, F., Stapleton, A.E. (2019). Plant growth regulators interact with elevated temperature to alter heat stress signaling via the Unfolded Protein Response in maize. *Scientific Reports*, 9(1), 10392.
39. Oleńska, E., Małek, W., Wójcik, M., Swiecicka, I., Thijs, S., Vangronsveld, J. (2020). Beneficial features of plant growth-promoting rhizobacteria for improving plant growth and health in challenging conditions: A methodical review. *Science of the Total Environment*, 743, 140682.
40. Orhan, E., Esitken, A., Ercisli, S., Turan, M., Sahin, F. (2006). Effects of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient contents in organically growing raspberry. *Scientia Horticulturae*, 111(1), 38-43.
41. Panchal, P., Preece, C., Peñuelas, J., Giri, J. (2022). Soil carbon sequestration by root exudates. *Trends in Plant Science*, 27(8), 749-757.
42. Pareek, A., Dhankher, O.P., Foyer, C.H. (2020). Mitigating the impact of climate change on plant productivity and ecosystem sustainability. *Oxford University Press*, UK, 71, 451-456.
43. Phillips, R.P., Finzi, A.C., Bernhardt, E.S. (2011). Enhanced root exudation induces microbial feedbacks to N cycling in a pine forest under long-term CO2 fumigation. *Ecology Letters*, 14(2), 187-194.
44. Prasad, R., Kumar, M., Varma, A. (2015). Role of PGPR in soil fertility and plant health. *Plant-Growth-Promoting Rhizobacteria (PGPR) and Medicinal Plants*, Springer, 247-260.
45. Prashar, P., Kapoor, N., Sachdeva, S. (2014). Rhizosphere: its structure, bacterial diversity and significance. *Reviews in Environmental Science and Bio/Technology*, 13(1), 63-77.
46. Shen, R., Lan, Z., Rinklebe, J., Nie, M., Hu, Q., Yan, Z., Fang, C., Jin, B., Chen, J. (2021). Flooding variations affect soil bacterial communities at the spatial and inter-annual scales. *Science of the Total Environment*, 759, 143471.
47. Shrivastava, U.P., Kumar, A. (2013). Characterization and optimization of 1-aminocyclopropane-1-carboxylate deaminase (ACCD) activity in different rhizospheric PGPR along with *Microbacterium* sp. strain ECI-12A. *International Journal of Applied Sciences and Biotechnology*, 1(1), 11-15.
48. Sivasakthi, S., Usharani, G., Saranraj, P. (2014). Biocontrol potentiality of plant growth promoting bacteria (PGPR)-*Pseudomonas fluorescens* and *Bacillus subtilis*: a review. *African Journal of Agricultural Research*, 9(16), 1265-1277.
49. Surówka, E., Rapacz, M., Janowiak, F. (2020). Climate change influences the interactive effects of simultaneous impact of abiotic and biotic stresses on plants. *Plant Ecophysiology and Adaptation under Climate Change: Mechanisms and Perspectives I: General Consequences and Plant Responses*, 1-50.
50. Ullah, A., Bano, A., Khan, N. (2021). Climate change and salinity effects on crops and chemical communication between plants and plant growth-promoting microorganisms under stress. *Frontiers in Sustainable Food Systems*, 5, 618092.
51. Veni, V.G., Srinivasarao, C., Reddy, K.S., Sharma, K., Rai, A. (2020). Soil health and climate change. *Climate Change and Soil Interactions*, Elsevier, 751-767.
52. Vivas, A., Marulanda, A., Ruiz-Lozano, J.M., Barea, J.M., Azcón, R. (2003). Influence of a *Bacillus* sp. on physiological activities of two arbuscular mycorrhizal fungi and on plant responses to PEG-induced drought stress. *Mycorrhiza*, 13, 249-256.
53. Vyas, P., Kumar, D., Dubey, A., Kumar, A. (2018). Screening and characterization of *Achromobacter xylosoxidans* isolated from rhizosphere of *Jatropha curcas* L. (energy crop) for plant-growth-promoting traits. *J Adv Res Biotechnol*. https://doi.org/10.15226/2475-4714/3/1/00134.
54. Yang, J., Kloepper, J.W., Ryu, C-M. (2009). Rhizosphere bacteria help plants tolerate abiotic stress. *Trends in Plant Science*, 14(1), 1-4.
55. Yazdani, M., Bahmanyar, M.A., Pirdashti, H., Esmaili, M.A. (2009). Effect of phosphate solubilization microorganisms (PSM) and plant growth promoting rhizobacteria (PGPR) on yield and yield components of corn (*Zea mays* L.). *World Academy of Science, Engineering and Technology*, 49, 90-92.
56. Zhang, J., Singh, D., Guo, C., Shang, Y., Peng, S. (2020a). Rhizobia at extremes of acidity, alkalinity, salinity, and temperature. *Microbial Versatility in Varied Environments: Microbes in Sensitive Environments*, 51-65.
57. Zhang, X., Chen, X., Liu, M., Xu, Z., Wei, H. (2020b). Coupled changes in soil organic carbon fractions and microbial community composition in urban and suburban forests. *Scientific Reports*, 10(1), 15933.

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