Plant-Microbe Interactions under the Extreme Habitats

Subjects: Biotechnology & Applied Microbiology

Contributor: Pragya Tiwari , Subir Kumar Bose , Kyeung-Il Park , Laurent Dufossé , Mireille Fouillaud

Plant-microbe associations define a key interaction and have significant ecological and biotechnological perspectives. In recent times, plant-associated microbes from extreme environments have been extensively explored for their multifaceted benefits to plants and the environment, thereby gaining momentum in global research. Plant-associated extremophiles highlight ubiquitous occurrences, inhabiting extreme habitats and exhibiting enormous diversity. The remarkable capacity of extremophiles to exist in extreme environmental conditions is attributed to the evolution of adaptive mechanisms in these microbes at genetic and physiological levels. In addition, the plant-associated extremophiles have a major impact in promoting plant growth and development and conferring stress tolerance to the host plant, thereby contributing immensely to plant adaptation and survival in extreme conditions.

biodiversity drought stress extremophiles phytohormones plant microbiome engineering

1. Introduction

Global fluctuations in climatic conditions and environment-induced stresses have a key impact on crop yield and productivity. Statistics have suggested that biotic and abiotic stress have a profound effect on agricultural productivity, with more than 60% of land affected by drought, 9% by deficiency of minerals, 57% of land by extreme cold, 15% by acidic soils, and 6% land by saline conditions [1][2]. To survive and adapt to changes in global climatic conditions, plants have evolved multiple, protective mechanisms to tackle these changes [3][4]. Plant-microbe interactions constitute an evolutionarily favored dynamic association forming an integral component of the ecosystem. Microbes thriving in extreme environments possess genetic and physiological features to survive in diverse and extreme environmental conditions [5][6]. Plant-associated microbes are reported from extreme environmental habitats, namely high and low temperatures, increased salinity, high and low pH, and drought conditions, among others [3][7]. The microbes present in extreme environmental niches are known as extremophiles and possess unique properties to grow and survive in such diverse conditions. Moreover, these microbes may thrive in extreme conditions such as hypersalinity (2–5 M NaCl, designated as halophiles), high and low temperatures (60–115 °C—known as thermophiles), (−2–20 °C—designated as psychrophiles) and diverse pH range (<4 acidophiles and >9 alkaliphiles), respectively [8]. The beneficial microbes associated with plants are classified as rhizospheric, epiphytic, or endophytic and demonstrate multi-faceted attributes from ecological and biotechnological perspectives [9][10].

The extremophiles associated with plants are classified as bacteria, archaea, and eukaryotes, and further into different groups, e.g., *Bacteroidetes*, *Ascomycota*, *Basidiomycota*, *Euryarchaeota*, *Firmicutes*, *Actinobacteria*, *Crenarchaeota*, and *Proteobacteria*. As the beneficial associate, the plant-associated extremophiles display multiple ecological and plant growth promotion (PGP) attributes, positively impacting their plant counterparts [11][12][13]. The plant-associated rhizospheric microbes are present in the root zone and key examples include *Paenibacillus*, *Burkholderia*, *Azospirillum*, *Bacillus*, *Methylobacterium*, and *Pseudomonas*, etc. [14][15], while the epiphytic microbes are present in different phyllosphere zones and may tolerate UV radiations and high-temperature conditions (40–55 °C). The representative examples inhabiting the phyllosphere comprise *Agrobacterium*, *Methylobacterium*, *Pantoea*, and *Pseudomonas*, isolated from different crops in moderate and extreme conditions [16]. The endophytic microbes colonize the internal plant tissues and exist in a mutualistic association with plants [17] and the key examples are *Achromobacter*, *Azoarcus*, *Enterobacter*, *Herbaspirillum*, *Burkholderia*, *Klebsiella*, *Nocardioides*, *Pantoea*, and others isolated from different plant species [18][19].

The recent era has witnessed the increased recognition of plant-associated microbes in key biotechnological applications including agriculture, ecosystem restoration, and areas of socio-economic concerns [20][21]. Rhizospheric microbes enhance plant tolerance to abiotic stress through various mechanisms, comprising phytohormone production, mineral solubilization, nitrogen fixation, and plant defense against several fungal and bacterial pathogens [14]. Biological nitrogen fixation by microbes is regarded as a key mechanism in the promotion of plant growth and rhizobacteria enhances plant growth by fixing atmospheric nitrogen into nitrate [22]. Moreover, archaea, root endophytic bacteria, and some rhizobacteria produce antimicrobial compounds that function as biocontrol agents against various pathogens [23]. The plant growth-promoting rhizobacteria (PGPR) are documented in extreme habitats and the key members include *Azospirillum* [24], *Pseudomonas* [25], *Enterobacter*, and *Klebsiella* [26][27], *Rhizobium* [26], *Bradyrhizobium* [28], *Bacillus* [29], *Burkholderia* [30], *Micrococcus* [31] and *Frankia* [32], respectively.

2. Dynamics of Plant-Microbe Interactions in Extreme Habitats

In the extreme environment, the microbes thrive in the plant vicinity and form symbiotic associations with their plant counterparts. Exhibiting diversity, the microbes are ubiquitous and perform diverse functions, including nutritional uptake, conferring tolerance to environmental stress, and promoting plant growth and development. The existence of microbes in extreme niches raises curiosity to explore the dynamics of symbiotic association, their environmental impact, and biotechnological utilities [33] (**Figure 1**).

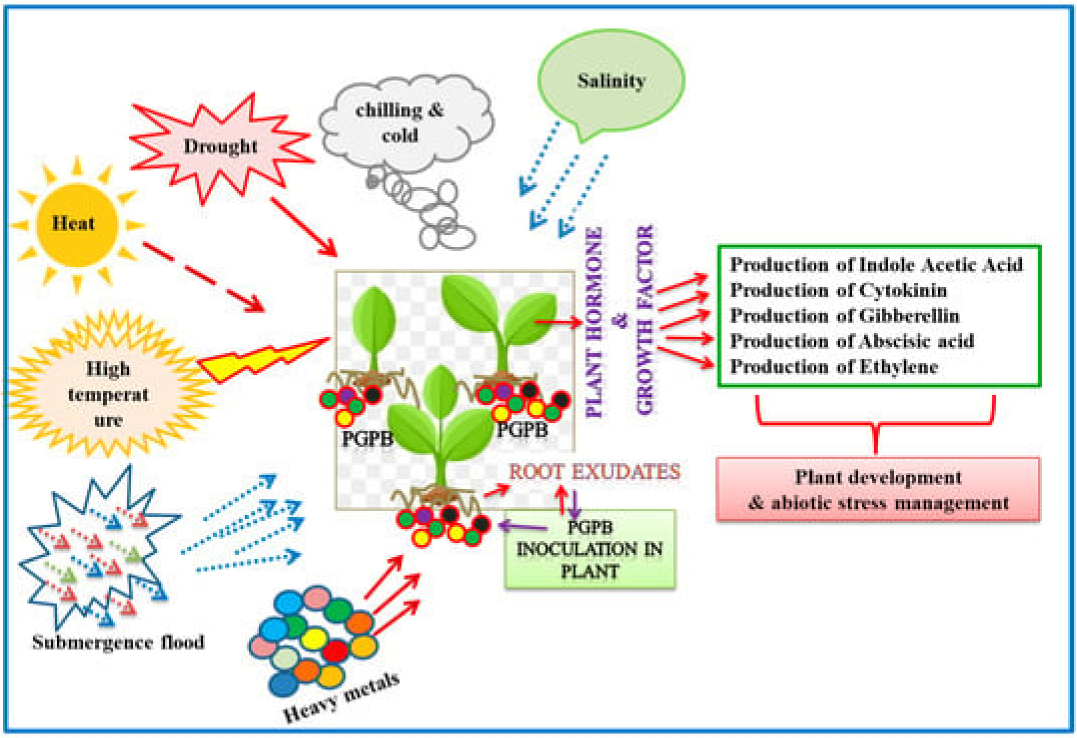

Figure 1. Diagrammatic representation of plant growth-promoting bacteria (endophytic, rhizospheric, and epiphytic) and functional attributes in impacting plant growth, development, and abiotic stress (viz. heat, drought, salinity, chilling, and flood) management.

In extreme habitats, the microbes have evolved distinct genetic and physiological mechanisms to survive and adapt to challenging environmental conditions [8][34]. To get a better understanding, microbes have been isolated and characterized from extreme environments by both culture-dependent and culture-independent techniques [7][35][36] and meta-omics approaches [37].

3. Diversity and Distribution of Plant-Associated Extremophiles

3.1. Epiphytic Microbiomes

The above-ground microbial communities (bacteria, fungi, and yeast) in plant association are referred to as the phyllospheric microbes [38]. The aerial zone inhabited by the microbes is known as phyllosphere and the microbes are designated as epiphytes. Mostly, the bacterial communities densely inhabit the leaf surface (epiphytes), however, leaf surface colonization by epiphytes represents a challenging zone for colonization [39][40]. The microbial communities colonizing leaves include different genera of bacteria, algae, filamentous algae, and protozoans. The bacterial species are the most abundant in the phyllosphere and are found in approximately 10^6 to 10^7 cells/cm^2 of the leaf [41]. The epiphytic bacterial communities exhibit size differences among plant species caused by the physical and nutritional condition of the phyllosphere [40]. Moreover, epiphytic microbes have distinct characteristics and show tolerance to high temperatures (40–55 °C) and ultraviolet radiation, being constantly exposed to adverse environmental conditions. Microbes from different phyllosphere zones of crops were reported: *Agrobacterium*, *Methylobacterium*, *Pantoea*, *Bacillus*, *Enterobacter*, and *Pseudomonas* comprising key microbial species in moderate and extreme environmental conditions [40]. Studies have suggested that leaf-colonizing bacteria promote plant growth and confer tolerance to environmental stresses [42].

3.2. Endophytic Microbiomes

Endophytes constitute bacterial or fungal microorganisms, inhabiting inter/intracellular spaces within plant tissues, and present in almost all plant species. Since plants restrict the growth of endophytes, endophytes evolve mechanisms for adaptation to the environment [43][44], including the production of metabolites for plant growth and development [9][10][11]. Endophytes have been isolated from different plant parts namely meristem, leaves [45], seeds [46], roots [36], and stem, among other tissues. However, studies have suggested that isolation of some endophytes is difficult, and different methods have been employed, namely plant tissue culture on suitable media [46] and endophyte isolation using surface sterilization of ground tissue extract [47]. The fungal endophytes from plants and algae are classified in *Ascomycetes*, while very few reports on *Basidiomycetes* are available [48]. Some of the microorganisms, namely *Penicillium glandicola*, *Acremonium terricola*, and *Phoma tropica*, were classified as fungal endophytes [49]. The endophytic microbial communities comprised of *Achromobacter*, *Azoarcus*, *Burkholderia*, *Enterobacter*, *Gluconoacetobacter*, *Herbaspirillum*, etc. were isolated from different plant species [17][18]. Plant endophyte associations have important ecological and biotechnological attributes [50][51][52].

3.3. Rhizospheric Microbiomes

The rhizospheric microbial communities present in extreme environments, i.e., drought, salinity, and acidity/alkalinity have developed adaptive mechanisms for survival and are characterized [26][53]. The microbial communities belonging to archaeal phyla *Euryarchaeota* and *Crenarchaeota* and bacterial phyla *Actinobacteria*, *Bacteroidetes*, *Proteobacteria*, and *Firmicutes*) were predominantly present in plant rhizosphere, in extreme habitats [54]. The *Proteobacteria* consist of *α/β/γ/δ-Proteobacteria*, found in close association with most of the crop plants. The agriculturally significant species comprise of *α-Proteobacteria* which requires low nutrients for growth and induces nitrogen fixation in plant symbiosis. The *β-Proteobacteria* have a high metabolic rate and the *γ-Proteobacteria* define the largest class, including *Azotobacter* and *Pseudomonas*. The genus *Azospirillum* is closely associated with crop plants namely *Amaranthus*, sorghum, sugarcane, maize, and ryegrass, demonstrating symbiotic nitrogen fixation [55].

4. Plant-Microbe Interactions in Extreme Ecological Habitats

4.1. Acidic Environment

Acidophiles comprise microbes that thrive in highly acidic environments, as low as pH < 3. Acidophiles are found in diverse ecological niches, including hydrothermal regions, volcanic areas, deep-sea vents, and the stomachs of animals [56][57]. High acidic conditions are found to adversely affect plant growth, leading to changes in the availability of nutrients and soil pH. The plant counters high acidic conditions by maintaining its internal pH. Diverse rhizospheric microbes inhabit acidic environments: acid-tolerant PGPB including *Acidithiobacillus*, *Flavobacterium*, *Lysinibacillus*, *Pseudomonas*, and *Methylobacterium* were isolated and characterized [58]. The best-characterized acidophiles are classified in Archea and bacterial domains [59]. The microbial communities associated with the crop plants are found to be essential for soil health and crop productivity [60][61] and siderophore production alleviates abiotic stress conditions.

4.2. Alkaline Environment

The microbes from alkaline environments can tolerate high pH (>9) and are known as alkaliphiles. These extremophiles possess genetic and physiological mechanisms to survive in harsh conditions. The rhizospheric zone of the plant colonizing alkaline environments such as *Smallanthus sonchifolius*, *Dichanthium annulatum*, and *Chrysanthemum morifolium* comprises diverse microbes from methane and hydrogen-rich environments [54]. In these alkaline conditions, microbes maintain cytoplasmic pH through protein and enzyme activity. Moreover, the alkaliphilic bacteria have the adaptive mechanism to tolerate a diverse range of pH 6–10, with pH 7–8 being optimum for growth [62].

4.3. Drought Condition

In adverse environmental conditions, plant adaptation and survival are promoted by AM fungi and PGP microbes [63]. In this regard, the drought-tolerant microbes have evolved to adapt/survive in water-deficit conditions and protect host plants by facilitating nutrient uptake and plant growth. The microbes colonize the rhizospheric zone and employ multiple direct or indirect mechanisms including the production of ACC deaminase, phytohormones (abscisic acid, cytokinins, and IAA), bacterial exopolysaccharides, and induced systemic tolerance [64].

The PGPR produces phytohormones that promote plant growth in stress conditions, for example, IAA governs the differentiation of vascular tissues, and cell division, and promotes the growth of shoots under drought stress [65]. On the other hand, the ABA hormone mitigates drought stress by increasing the transcription of drought-linked genes [66]. ACC deaminase (from bacteria) hydrolyzes ACC into alphaketobutyrate and ammonia [67]. The PGP and drought-tolerant bacteria enhance water potential, and biomass, thereby minimizing water loss in drought conditions [68]. The rhizospheric microbes produce exopolysaccharides and alleviate drought stress in plants [69]. In *Lycopersicum esculentum*, phytohormone strigolactone production was increased on *Rhizophagus irregularis* colonization and exposure to drought, showing a signaling mechanism of the phytohormone in increasing drought tolerance [70]. The drought-resistant rhizobacteria modulate phytohormones and confer drought tolerance- PGPRs (*Acinetobacter*, *Bacillus thuringiensis*, *Azospirillum*, etc.) synthesize IAA that alters root architecture by augmenting root surface area and root tips, nutrient acquisition, and aid plant in overcoming drought [71][72].

4.4. High Temperature

High-temperature conditions adversely affect plant growth by altering membrane permeability, seed germination, and rate of photosynthesis [73]. The rhizospheric microbes of plants inhabiting extremely high temperatures, *Triticum aestivum*, *Cupressus dupreziana*, and *Sporobolus indicus*, promote plant growth in hot conditions. PGPB increases plant growth through several mechanisms, comprising nitrogen fixation, solubilization of P, and Zn, phytohormone production, HCN, and siderophore production [74]. Due to the ability of PGPB in plant growth, many bacterial genera namely *Arthrobacter*, *Streptomyces*, *Pseudomonas*, and *Staphylococcus* sp. are used as bioformulations for plant growth in high-temperature conditions. In high temperatures, the metabolism and physiology of extremophiles are adversely affected, and the microbial enzymes promote high-temperature acclimatization and protection of cell structure and integrity via increased expression of heat-tolerant proteins [8]. Several fungal species have been isolated from hot habitats and comprise *Talaromyces thermophilus*, *T. byssochlamydoides*, *Malbranchea cinnamomea*, *Aspergillus terreus*, *Myceliophthora fergusii*, *Thermomyces lanuginosus* [75], *Myceliophthora thermophila* [76], *Scytalidium thermophilum* [77], and others [78]. The fungal communities protect the plant by performing several functions, which include P, potassium (K), and Zn solubilization, phytohormone production, and siderophore production for plant adaptation and survival [60][61][79].

4.5. Low Temperature

The microbes inhabiting extremely cold temperatures are designated as psychrotrophic microbes and have prospects in medicine, agriculture, and industries. Microbes from cold habitats are universally present, found in mountain caps, glaciers, frozen lakes, and snow, and in association with plants growing in cold habitats. Diverse microbes were isolated by culture-dependent and culture-independent techniques and classified as *viz.*, *Euryarchaeota*, *Ascomycota*, *Basidiomycota*, *Chlamydiae*, *Cyanobacteria*, *Actinobacteria*, *Chloroflexi*, *Bacteroidetes*, etc. [80]. The microbes inhabiting cold climates define importance in the ecological perspective since a considerable portion of aquatic and terrestrial ecosystems are influenced by cold temperatures. Moreover, cold regions extremophiles have been reported from Antarctica and extreme cold regions of the world. The extremophiles show extreme diversity and novel psychrophilic microbes comprise *Oleispira antarctica* [81], *Flavobacterium frigidarium* [82], *Octadecabacter arcticus* [83], *Sphingomonas glacialis* [84], *Halobacterium lacusprofundi* [85], and *Cellulophaga algicola* [86].

4.6. Saline Condition

Globally, most of the land in agriculture is threatened by the presence of saline conditions that result in poor microbial functions, due to osmotic stress and ion-induced toxicity [64] detrimental to plant growth. Moreover, soil salinity adversely affects the plants including seed germination, uptake of nutrients and water, crop productivity, and ecological balance [87]. Several studies demonstrated the beneficial effect of PGP and endophytic microbes in mitigating the negative effect of salinity in soil [88]. In a key example, the PGPB *Pseudomonas stutzeri*, when inoculated in salt-sensitive and tolerant plants, reduced the adverse effects [89]. Sometimes, inoculation of salt-tolerant bacteria together with AM fungi considerably improves the plant tolerance to salinity stress [90]. Salinity-tolerant microbes adopt several direct and indirect mechanisms to counter salinity stress, and these include the production of phytohormones, mobilization of nutrients, nitrogen fixation, and siderophore production [91]. These microbial mechanisms contribute to root length increase, number of roots, and surface area by uptake of nutrients [92].

4.7. Presence of Heavy Metals

The presence of heavy metals in agrosystems has intensified across the globe and the high concentration of heavy metals is toxic and adversely impacts plant growth and functions. The decrease in crop yield affects human health and food demands, cadmium (Cd) and lead (Pb) are the major toxic heavy metals affecting *O. sativa*, a staple food crop. In addition, the accumulation of heavy metals in crops can cause serious health damage.

In recent times, heavy metal stress alleviation employing microbes is gaining importance, and key examples include *Pseudoalteromonas* sp., *Bacillus*, *Salmonella* sp. [93][94][95]. In heavy metal-stress plants, rhizobacteria produce IAA and elevate plant growth in polluted soil via macro and micronutrient uptake and conferring plant tolerance to heavy metals [72]. An interesting example is *Deinococcus radiodurans*, an extremophile bacterium that occurs in soil [96]. The bacteria have a high concentration of Mn^{2+}-metabolite complexes that can scavenge ROS [97]. The inoculation of rice plants with the bacteria releases antioxidants that improve plant tolerance to Pb and Cd stress.

4.8. Flooding Condition

In the fluctuating climate scenario, the increase in flood conditions poses havoc for land plants and causes flooding stress. The flooding stress adversely impacts the plants and causes metabolic and physiological changes and alters the plant-associated microbiome. The nature-based solutions to tackle flooding stress utilize living organisms to minimize the effects of climatic fluctuations [98][99].

5. Biotechnological Applications of Plant Microbiome

5.1. Plant Growth Promotion

5.1.1. Production of Phytohormones

Phytohormones play an integral role in affecting plant growth dynamics via multiple physiological and biochemical changes in the plant life cycle [100][101]. In the mitigation of biotic and abiotic stresses, PGPB found in the rhizospheric zone secretes many phytohormones and modulates the concentration of specific growth hormones in the plant [102]. In the rhizospheric zone, different rhizosphere colonizing bacteria were shown to produce phytohormones to enhance plant growth [103][104]. Phytohormones are chemical messengers that in small amounts regulate cellular activities, key examples include abscisic acid, cytokinin, auxins, brassinosteroids, and jasmonates, etc. and some are key targets for plant metabolic engineering for conferring abiotic stress tolerance [105][106]. *Cucumis sativus* root secretes vanillic acid and p-coumaric acid which demonstrate differential effects on the soil microbiome.

Rhizosphere colonizing or endophytic ACC deaminase-producing bacteria alters plant ethylene levels [107]. Abscisic acid (ABA) greatly assists plants in countering environmental stresses and is actively involved in various defense mechanisms. Shahzad et al. [108] investigated the favorable impact of *Bacillus amyloliquefaciens* inoculation in rice on plant growth attributes in salinity conditions.

5.1.2. Biological Nitrogen Fixation

Nitrogen is a very important element for plant growth since it plays a major role in amino acid synthesis, the key building blocks of proteins, and is a major component of chlorophyll, an important pigment for photosynthesis. It is also found in other important biomolecules, such as nitrogen bases including nucleotides and nucleosides (ATP, GTP, CTP, and TTP, etc.) and nucleic acids. Prokaryotic organisms possess a widespread ability to fix atmospheric nitrogen [109]. PGPB positively impacts plant growth via- direct mechanisms, including multiple processes such as nitrogen fixation, phosphate solubilization, production of siderophore, ammonia, and phytohormones, etc. while the indirect mechanisms comprise antibiotic production, ACC deaminase activity, induced systemic resistance (ISR) among others [110].

5.1.3. Mineral Solubilization

Plant well-being is greatly influenced by mineral nutrients and during abiotic stress, plants are unable to absorb the minerals and micronutrients severely hampering plant growth and leading to plant disease. The above damages are corrected naturally by microbes that can convert complex forms to simple forms that are easily absorbed by the plants (e.g., siderophores). Siderophores are produced by bacteria, fungi, and plants to facilitate the uptake of iron [111][112] and function as iron chelators (bind iron present in the rhizosphere).

The poor availability of inorganic phosphate (orthophosphate) in soil hampers crop production [113]. The phosphate solubilizing bacteria converts insoluble inorganic phosphate [114] to soluble forms and improves phosphorous availability for the plant. Joe and coworkers [115] isolated *Acinetobacter* sp. and *Bacillus* sp. from *Phyllanthus amarus* which showed phosphate solubilization and salt tolerance and increased plant growth compared to non-inoculated plants.

5.1.4. Biocontrol Function

Biocontrol agents secrete biochemical and other substances and inhibit harmful pathogenic bacteria without damaging plants and soil. The plants/crops are disease-affected by reducing crop yields, contamination of food grains, and declining production quality. Multiple PGPB synthesizes salicylic acid that signals systemic acquired resistance (SAR) while PGPB may start to induce systemic resistance (ISR), enhancing plant defense against plant pathogens [116]. PGPBs are key players in disease management, maintain ecological subsistence, and reduce the deleterious effects of chemical fertilizers [117][118]. The representative examples include *Arthrobacter*, *Enterobacter*, *Pseudomonas*, *Rhizobium*, and *Frankia* spp.

5.2. Mitigation of Multiple Abiotic Stress

Recent agricultural trials have scientifically validated that PGPRs not only reduce environmental stresses but also increase the production of a variety of crop plants, such as soybeans, mint, rice, barley, and maize [91][119][120][121].

Hormones primarily control the prioritization of signals carried out by protein switches such as kinases, transcription factors (TFs), and G-proteins, according to molecular research (gene expression profiling). Usually, plants focus their physiological resources on abiotic stress adaptation, which renders them prone to biotic stressors such as herbivory and disease [122].

The hormone that is primarily involved in the abiotic stress response is ABA. Plants respond to abiotic stress through defense mechanisms activated by ethylene, salicylic acid, or jasmonate [123].

Microbe-mediated development of abiotic stress responses is often referred to as induced systemic tolerance (IST). Over the past few decades, there has been a lot of research conducted regarding the function that microbes play in helping plants cope with abiotic challenges [124]. Plants experience less abiotic stress thanks to the possible inherent metabolic and genetic capacities of microbes [102][116]. *T. harzianum* function in the rice genotype decreases stress through the overexpression of physiological genes, specifically those encoding aquaporin, dehydrin, and malondialdehyde [125]. The rhizosphere makes up a soil microclimate around the root zone, where the average number of microbes is significantly higher than in the bulk soil. Therefore, it is evident that a variety of nutrients, minerals, and metabolites found in plant roots may play a significant role in drawing microbes to gather and form partnerships with plants.

5.2.1. Heat Stress

The microbes belonging to different genera including *Azospirillum*, *Achromobacter*, *Variovorax*, *Enterobacter*, *Bacillus*, *Azotobacter*, *Klebsiella*, *Aeromonas,* and *Pseudomonas* promote plant growth under heat conditions [126]. *T. aestivum* inoculated with *Azospirillum brasilence*, and *Bacillus amyloliquefaciens*, under heat stress resulted in reduced regeneration of ROS (reactive oxygen species), pre-activation of heat shock transcription factors, and changes in metabolome [127].

5.2.2. Cold Stress

The freezing (cold) damage is one of the main causes of crop loss [128][129]. It lowers crop production and productivity by slowing down plant growth and development [130][131]. PGPRs are beneficial to many plants as they increase their resistance to various stressors, such as low temperatures. Su et al. [132] showed that *Burkholderia phytofirmans* PsJN decreased the effect of freezing temperatures on *A. thaliana* photosynthesis.

5.2.3. Drought Stress

According to Mittler et al. [133] and Cramer et al. [2], agricultural loss occurs in different crops due to abiotic stress namely water deficit (drought) conditions, and affects 64% of the global land area, respectively. The potential of microbial interactions with the plants has, therefore, multifaceted functions, one of them is adaptation under drought stress. The root fungal endophyte *Piriformospora indica* induces drought tolerance in Chinese cabbage by increasing the levels of antioxidants and improving many physiological parameters [134].

5.2.4. Salinity Stress

T. harzianum application to increase the oil content in NaCl-affected Indian mustard (*Brassica juncea*), improved nutrient uptake, and improved the accumulation of antioxidants and osmolytes while decreasing NaCl uptake [135]. Concurrent with these results, it was shown that plants treated with *Trichoderma* produced higher levels of monodehydroascorbate reductase. Additionally, research on mutants has verified that *Trichoderma* produces ACC-deaminase, which reduces the effects of salt stress [136]. *Pseudomonas* sp. and *Acinetobacter* sp. have been shown to increase the production of IAA and ACC deaminase in salt-affected soil in oats and barley [137]. *B. phytofirmans* strain PsJN mitigates drought stress in maize [138], wheat [139], and salt stress in *Arabidopsis* [140]. Salt tolerance in rice variety improved in germination under salinity stress via *Pseudomonas* sp. inoculation.

References

1. Bui, E.N. Soil salinity: A neglected factor in plant ecology and biogeography. J. Arid. Environ. 2013, 92, 14–25.
2. Cramer, G.R.; Urano, K.; Delrot, S.; Pezzotti, M.; Shinozaki, K. Effects of abiotic stress on plants: A systems biology perspective. BMC Plant Biol. 2011, 11, 163.
3. Shu, W.S.; Huang, L.N. Microbial diversity in extreme environments. Nat. Rev. Microbiol. 2022, 20, 219–235.
4. Singh, B.K.; Delgado-Baquerizo, M.; Egidi, E.; Guirado, E.; Leach, J.E.; Liu, H.; Trivedi, P. Climate change impacts on plant pathogens, food security, and paths forward. Nat. Rev. Microbiol. 2023, 21, 640–656.
5. Dance, A. Studying life at the extremes. Nat. Vol. 2020, 587, 165–166.
6. Singh, S. A review on possible elicitor molecules of cyanobacteria: Their role in improving plant growth and providing tolerance against biotic or abiotic stress. J. Appl. Microbiol. 2014, 117, 1221–1244.
7. Talib, K.M.; Luhuai, J.; Chen, X.; Akbar, A.; Tahir, A.; Iqbal, I.; Ali, I. Isolation, culture, and maintenance of Extremophilic fungi. In Extremophilic Fungi; Sahay, S., Ed.; Springer: Singapore, 2022.
8. Uzilday, R.O.; Ganie, S.A. Editorial: Extremophiles: Tolerance mechanisms and use in crop improvement. Front. Plant Sci. 2023, 14, 1233202.
9. Tiwari, P.; Bae, H. Trends in Harnessing Plant Endophytic microbiome for mitigation of heavy metal toxicity in Plants-a perspective. Plants 2023, 12, 1515.
10. Tiwari, P.; Kang, S.; Bae, H. Plant-endophyte associations, rich yet under-explored sources for novel bioactive compounds and applications. Microbiol. Res. 2023, 266, 127241.

11. Bose, S.K.; Bajpai, M.; Das, J.; Gautam, A.; Tiwari, P. Actinomycetes endophytes: Overview and significance in the production of bioactive compounds. In Endophytes: Types, Potential Uses, and Mechanisms of Action; Tiwari, P., Ed.; Nova Publishers: Hauppauge, NY, USA, 2022; ISBN 979-8-88697-045-6.
12. Roy, B.; Maitra, D.; Ghosh, J.; Mitra, A.K. Unique extremophilic Bacillus: Their application in plant growth promotion and sustainable agriculture. In Microbes and Microbial Biotechnology for Green Remediation; Malik, J.S., Ed.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 287–304.
13. Adil, M.; Tiwari, P.; Chen, J.T.; Khan, R.N.; Kanwal, S. Major bioactive metabolites and antimicrobial potential of Orchidaceae Fungal endophytes. In Advances in Orchid Biology, Biotechnology, and Omics; Tiwari, P., Chen, J., Eds.; Springer Publishers: Berlin/Heidelberg, Germany, 2023; ISBN 13-978-9819910786.
14. Dlamini, S.P.; Akanmu, A.O.; Babalola, O.O. Rhizospheric microorganisms: The gateway to sustainable plant health. Front. Sustain. Food Syst. 2022, 6, 925802.
15. Lavania, M.; Chauhan, P.S.; Chauhan, S.V.S.; Singh, H.B.; Nautiyal, C.S. Induction of plant defense enzymes and phenolics by treatment with plant growth–promoting rhizobacteria Serratia marcescens NBRI1213. Curr. Microbiol. 2006, 52, 363–368.
16. Nutaratat, P.; Srisuk, N.; Arunrattiyakorn, P.; Limtong, S. Plant growth-promoting traits of epiphytic and endophytic yeasts isolated from rice and sugar cane leaves in Thailand. Fungal Biol. 2014, 118, 683–694.
17. Tiwari, P. Endophytes: Types, Potential Uses, and Mechanisms of Action; Nova Publishers: Hauppauge, NY, USA, 2022; ISBN 979-8-88697-045-6.
18. Ryan, R.P.; Germaine, K.; Franks, A.; Ryan, D.J.; Dowling, D.N. Bacterial endophytes: Recent developments and applications. FEMS Microbiol. Lett. 2008, 278, 1–9.
19. Tiwari, P.; Muhammad, A.; Bae, H. Endophyte-mediated bioremediation–an efficient biological strategy in ecological subsistence and agriculture. In Endophytic and Arbuscular Mycorrhizal Fungi and Their Role in Sustainable Agriculture; Erwin, D.J., Ed.; Nova Publishers: Hauppauge, NY, USA, 2023; ISBN 979-8-88697-766-0.
20. Tiwari, P.; Mishra, B.N.; Sangwan, N.S. β-glucosidases from the fungus Trichoderma: Efficient cellulose machinery in biotechnological application. BioMed. Res. Int. 2013, 2023, 203735.
21. Tiwari, P.; Dufosse, L. Focus and insights into the synthetic biology-mediated chassis of economically important fungi for the production of high-value metabolites. Microorganisms 2023, 11, 1141.
22. Rucker, H.R.; Kaçar, B. Enigmatic evolution of microbial nitrogen fixation: Insights from Earth’s past. Trends Microbiol. 2023, 23, 91–94.

23. Saeed, Q.; Xiukang, W.; Haider, F.U.; Kučerik, J.; Mumtaz, M.Z.; Holatko, J.; Naseem, M.; Kintl, A.; Ejaz, M.; Naveed, M.; et al. Rhizosphere bacteria in plant growth promotion, biocontrol, and bioremediation of contaminated sites: A comprehensive review of effects and mechanisms. Int. J. Mol. Sci. 2021, 22, 10529.
24. Fukami, J.; Cerezini, P.; Hungria, M. Azospirillum: Benefits that go far beyond biological nitrogen fixation. AMB Express 2018, 8, 73.
25. Ali, B.; Sabri, A.N.; Ljung, K.; Hasnain, S. Auxin production by plant-associated bacteria: Impact on endogenous IAA content and growth of Triticum aestivum L. Lett. Appl. Microbiol. 2009, 48, 542–547.
26. Sorty, A.M.; Meena, K.K.; Choudhary, K.; Bitla, U.M.; Minhas, P.S.; Krishnani, K.K. Effect of plant growth promoting bacteria associated with halophytic weed (Psoralea corylifolia L.) on germination and seedling growth of wheat under saline condi-tions. Appl. Biochem. Biotechnol. 2016, 180, 872–882.
27. Mukhtar, S.; Shahid, I.; Mehnaz, S.; Malik, K.A. Assessment of two carrier materials for phosphate solubilizing biofertilizers and their effect on the growth of wheat (Triticum aestivum L.). Microbiol. Res. 2017, 205, 107–117.
28. Panlada, T.; Pongdet, P.; Aphakorn, L.; Rujirek, N.N.; Nantakorn, B.; Neung, T. Alleviation of the effect of environmental stresses using co-inoculation of mungbean by Bradyrhizobium and Rhizobacteria containing stress-induced ACC deaminase enzyme. Soil Sci. Plant Nut. 2013, 59, 559–571.
29. Mukhtar, S.; Mehnaz, S.; Mirza, M.S.; Mirza, B.S.; Malik, K.A. Diversity of Bacillus-like bacterial community in the rhizospheric and non-rhizospheric soil of halophytes (Salsola stocksii and Atriplex amnicola), and characterization of osmoregulatory genes in halophilic Bacilli. Can. J. Microbiol. 2018, 64, 567–579.
30. Barka, A.; Nowak, E.; Clément, C.J. Enhancement of chilling resistance of inoculated grapevine plantlets with a plant growth-promoting rhizobacterium, Burkholderia phytofirmans strain PsJN. Appl. Environ. Microbiol. 2006, 72, 7246–7252.
31. Dastager, S.G.; Deepa, C.K.; Pandey, A. Isolation and characterization of novel plant growth promoting Micrococcus sp. NII-0909 and its interaction with cowpea. Plant Physiol. Biochem. 2010, 48, 987–992.
32. Tani, C.; Sasakawa, H.; Takenouchi, K. Isolation of endophytic Frankia from root nodules of Casuarina equisetifolia and infec-tivity of the isolate to host plants. Soil Sci. Plant Nutr. 2003, 49, 137–142.
33. Singh, S.; Kumar, V.; Singh, S.; Dhanjal, D.S.; Datta, S.; Singh, J. Global scenario of plant–microbiome for sustainable agriculture: Current advancements and future challenges. In Plant

Microbiomes for Sustainable Agriculture, Sustainable Development and Biodiversity; Yadav, A.N., Ed.; Springer Nature: Cham, Switzerland, 2020.

34. Rekadwad, B.; Li, W.J.; Gonzalez, J.M.; Devasya, R.P.; Bhagwath, A.A.; Urana, R.; Parwez, K. Extremophiles: The species that evolve and survive under hostile conditions. 3 Biotech 2023, 13, 316.
35. Wejse, P.L.; Ingvorsen, K.; Mortensen, K.K. Purification and characterization of two extremely halotolerant xylanases from a novel halophilic bacterium. Extremophiles 2003, 7, 423–431.
36. Bajpai, M.; Das, J.; Tiwari, P. Molecular and biochemical methods for identification, isolation, and characterization of Endophytes. In Endophytes: Types, Potential Uses, and Mechanisms of Action; Tiwari, P., Ed.; Nova Publishers: Hauppauge, NY, USA, 2022; ISBN 979-8-88697-045-6.
37. Taş, N.; de Jong, A.E.E.; Li, Y.; Trubl, G.; Xue, Y.; Dove, N.C. Metagenomic tools in microbial ecology research. Curr. Opin. Biotechnol. 2021, 67, 184–191.
38. Bashir, I.; War, A.F.; Rafiq, I.; Reshi, Z.A.; Rashid, I.; Shouche, Y.S. Phyllosphere microbiome: Diversity and functions. Microbiol. Res. 2022, 254, 126888.
39. Remus-Emsermann, M.N.P.; Lücker, S.; Müller, D.B.; Potthoff, E.; Daims, H.; Vorholt, J.A. Spatial distribution analyses of natural phyllosphere-colonizing bacteria on Arabidopsis thaliana revealed by fluorescence in situ hybridization. Environ. Microbiol. 2014, 16, 2329–2340.
40. Schlechter, R.O.; Miebach, M.; Remus-Emsermann, M.N.P. Driving factors of epiphytic bacterial communities: A review. J. Adv. Res. 2019, 19, 57–65.
41. Lindow, S.E.; Brandl, M.T. Microbiology of the Phyllosphere. Appl. Environ. Microbiol. 2003, 69, 1875–1883.
42. Mendes, R.; Garbeva, P.; Raaijmakers, J.M. The rhizosphere microbiome: Significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS Microbiol. Rev. 2013, 37, 634–663.
43. Sridhar, K.R. Diversity, ecology, and significance of fungal endophytes. In Endophytes and Secondary Metabolites; Jha, S., Ed.; Springer Nature: Cham, Switzerland, 2019; pp. 61–100.
44. Tiwari, P.; Bae, H. Horizontal gene transfer and Endophytes: An implication for the acquisition of novel traits. Plants 2020, 9, 305.
45. Hata, K.; Sone, K. Isolation of endophytes from leaves of Neolitsea sericin broadleaf and conifer stands. Mycoscience 2008, 49, 229–232.
46. Ganley, R.J.; Newcombe, G. Fungal endophytes in seeds and needles of Pinus monticola. Mycol. Res. 2006, 110, 318–327.

47. Rai, R.P.; Dash, P.K.; Prasanna, B.M.; Singh, A. Endophytic bacterial flora in the stem tissue of tropical maize (Zea mays L.) genotype: Isolation, identification, and enumeration. World J. Microbiol. Biotechnol. 2007, 23, 853–858.
48. Rungjindamai, N.; Pinruan, U.; Choeyklin, R.; Hattori, T.; Jones, E.B.G. Molecular characterization of Basidiomycetous endophytes isolated from leaves, rachis, and petioles of the oil palm, Elaeis guineensis, in Thailand. Fungal Divers. 2008, 33, 139–161.
49. Bezerra, J.D.P.; Santos, M.G.S.; Svedese, V.M.; Lima, D.M.; Fernandes, M.J.; Paiva, L.M.; Souza-Motta, C.M. Richness of endophytic fungi isolated from Opuntia ficus-indica Mill. (Cactaceae) and preliminary screening for enzyme production. World J. Microbiol. Biotechnol. 2012, 28, 1989–1995.
50. Tiwari, P.; Srivastava, Y.; Bae, H. Trends of pharmaceutical design of Endophytes as anti-infective. Curr. Top. Med. Chem. 2021, 21, 1572–1586.
51. Tiwari, P.; Mohd, A.; Basavegowda, N.; Chen, J. Plant-associated endophytes: Molecular mechanisms and significance in promoting sustainable agriculture. In Endophytes: Types, Potential Uses, and Mechanisms of Action; Tiwari, P., Ed.; Nova Publishers: Hauppauge, NY, USA, 2022; ISBN 979-8-88697-045-6.
52. Tiwari, P.; Bae, H. Endophytic fungi: Insights, prospects, and challenges in natural product drug discovery. Microorganisms 2022, 10, 360.
53. Farrar, K.; Bryant, D.; Cope-Selby, N. Understanding and engineering beneficial plant–microbe interactions: Plant growth pro motion in energy crops. Plant Biotechnol. J. 2014, 12, 1193–1206.
54. Mukhtar, S.; Mehnaz, S.; Malik, K.A. Microbial diversity in the rhizosphere of plants growing under extreme environments and its impact on crop improvement. Environ. Sustain. 2019, 2, 329–338.
55. Steenhoudt, O.; Vanderleyden, J. Azospirillum, a free-living nitrogen-fixing bacterium closely associated with grasses: Genetic, biochemical and ecological aspects. FEMS Microbiol. Rev. 2000, 24, 487–506.
56. Gómez, F. Acidophile. In Encyclopedia of Astrobiology; Gargaud, M., Amils, R., Quintanilla, J.C., Cleaves, H.J., Irvine, W.M., Pinti, D.L., Viso, M., Eds.; Springer: Berlin/Heidelberg, Germany, 2011.
57. Feliatra, F.; Lukistyowati, I.; Yoswaty, D.; Rerian, H.; Melina, D.; Hasyim, W.; Nugroho, T.T.; Fauzi, A.R.; Yolanda, R. Phylogenetic analysis to compare populations of acid-tolerant bacteria isolated from the gastrointestinal tract of two different prawn species Macrobrachium rosenbergii and Penaeus monodon. AACL Bioflux 2016, 9, 360–368.
58. Dang, P.; Yu, X.; Le, H.; Liu, J.; Shen, Z.; Zhao, Z. Effects of stand age and soil properties on soil bacterial and fungal community composition in Chinese pine plantations on the Loess Plateau. PLoS ONE 2017, 12, e0186501.

59. Madigan, M.; Martinko, J. Brock Biology of Microorganisms, 11th ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2005; ISBN 0-13-144329-1.
60. Tiwari, P.; Bajpai, M.; Singh, L.K.; Yadav, A.; Bae, H. Portraying fungal mechanisms in stress tolerance: Perspective for sustainable agriculture. In Recent Trends in Mycological Research, Vol 1: Agricultural and Medical Perspective; Yadav, A.N., Ed.; Springer: Berlin/Heidelberg, Germany, 2021; pp. 269–292. ISBN 978-3-030-60658-9.
61. Tiwari, P.; Bajpai, M.; Singh, L.K.; Mishra, S.; Yadav, A.N. Phytohormones producing fungal communities: Metabolic engineering for abiotic stress tolerance in plants. In Agriculturally Important Fungi for Sustainable Agriculture; Gupta, V.K., Maria Tuohy, M., Eds.; Springer: Cham, Switzerland, 2020; pp. 171–197. ISBN 978-3-030-45970-3.
62. Borkar, S. Alkaliphilic Bacteria: Diversity, Physiology and Industrial Applications. In Bioprospects of Coastal Eubacteria; Borkar, S., Ed.; Springer: Cham, Switzerland, 2015.
63. Nadeem, S.M.; Ahmad, M.; Zahir, Z.A.; Javaid, A.; Ashraf, M. The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnol. Adv. 2014, 32, 429–448.
64. Kumar, A.; Verma, J.P. Does plant-microbe interaction confer stress tolerance in plants: A review? Microbiol. Res. 2018, 207, 41–52.
65. Goswami, D.; Thakker, J.N.; Dhandhukia, P.C. Simultaneous detection and quantification of indole-3-acetic acid (IAA) and indole-3-butyric acid (IBA) produced by rhizobacteria from l-tryptophan (Trp) using HPTLC. J. Microbiol. Method 2015, 110, 7–14.
66. Jiang, S.; Zhang, D.; Wang, L.; Pan, J.; Liu, Y.; Kong, X.; Zhou, Y.; Li, D. A maize calcium-dependent protein kinase gene, ZmCPK4, positively regulated abscisic acid signaling and enhanced drought stress tolerance in transgenic Arabidopsis. Plant Physiol. Biochem. 2013, 71, 112–120.
67. Bal, H.B.; Nayak, L.; Das, S.; Adhya, T.K. Isolation of ACC deaminase producing PGPR from rice rhizosphere and evaluating their plant growth promoting activity under salt stress. Plant Soil 2013, 366, 93–105.
68. Vardharajula, S.; Ali, S.Z.; Grover, M.; Reddy, G.; Bandi, V. Drought-tolerant plant growth promoting Bacillus spp.: Effect on growth osmolytes, and antioxidant status of maize under drought stress. J. Plant Interact. 2011, 6, 1–14.
69. Naseem, H.; Ahsan, M.; Shahid, M.A.; Khan, N. Exopolysaccharides producing rhizobacteria and their role in plant growth and drought tolerance. J. Basic Microbiol. 2018, 58, 1009–1022.
70. Omae, N.; Tsuda, K. Plant-microbiota interactions in abiotic stress environments. MPMI 2022, 35, 511–526.

71. Rolli, E.; Marasco, R.; Vigani, G.; Ettoumi, B.; Mapelli, F.; Deangelis, M.L.; Gandolfi, C.; Casati, E.; Previtali, F.; Gerbino, R. Improved plant resistance to drought is promoted by the root-associated microbiome as a water stress-dependent trait. Environ. Microbiol. 2015, 17, 316–331.
72. Etesami, H.; Maheshwari, D.K. Use of plant growth promoting rhizobacteria (PGPRs) with multiple plant growth promoting traits in stress agriculture: Action mechanisms and future prospects. Ecotoxicol. Environ. Saf. 2018, 156, 225246.
73. Xu, Z.; Shimizu, H.; Ito, S.; Yagasaki, Y.; Zou, C.; Zhou, G.; Zheng, Y. Effects of elevated CO2, warming and precipitation change on plant growth, photosynthesis, and peroxidation in dominant species from North China grassland. Planta 2014, 239, 421–435.
74. Mukhtar, S.; Ishaq, A.; Hassan, S.; Mehnaz, S.; Mirza, M.S.; Malik, K.A. Comparison of microbial communities associated with halophyte (Salsola stocksii) and non-halophyte (Triticum aestivum) using culture-independent approaches. Pol. J. Microbiol. 2017, 66, 375–386.
75. Maijala, P.; Kango, N.; Szijarto, N.; Viikari, L. Characterization of hemicellulases from thermophilic fungi. Antonie Van Leeuwenhoek 2012, 101, 905–917.
76. de Cassia Pereira, J.; Paganini Marques, N.; Rodrigues, A.; Brito de Oliveira, T.; Boscolo, M.; Da Silva, R.; Gomes, E.; Bocchini Martins, D.A. Thermophilic fungi as new sources for the production of cellulases and xylanases with potential use in sugarcane bagasse saccharification. J. Appl. Microbiol. 2015, 118, 928–939.
77. Yang, X.; Zhang, J.; Ding, Q.; He, Z.-C.; Zhu, C.Y.; Zhang, K.-Q.; Niu, X.-M. Metabolites from two dominant thermophilic fungal species Thermomyces lanuginosus and Scytalidium thermophilum. Chemi. Biodiver. 2020, 17, e2000137.
78. Sandona, K.; Billingsley Tobias, T.L.; Hutchinson, M.I.; Natvig, D.O.; Porras-Alfaro, A. Diversity of thermophilic and thermotolerant fungi in corn grain. Mycologia 2019, 111, 719–729.
79. Tiwari, P.; Bose, S.K.; Bae, H. Plant growth promoting soil microbiomes: Beneficial attributes and potential applications. In Soil Microbiomes for Sustainable Agriculture—Volume 2: Functional Annotation; Sustainable Development, and Biodiversity; Yadav, A.N., Ed.; Springer: Cham, Switzerland, 2021; Volume 27, pp. 1–30. ISBN 978-3-030-73506-7.
80. Kanekar, P.P.; Kanekar, S.P. Psychrophilic, Psychrotrophic, and Psychrotolerant microorganisms. In Diversity and Biotechnology of Extremophilic Microorganisms from India. Microorganisms for Sustainability; Kanekar, P.P., Kanekar, S.P., Eds.; Springer: Singapore, 2022.
81. Yakimov, M.M.; Giuliano, L.; Gentile, G.; Crisafi, E.; Chernikova, T.N.; Abraham, W.-R.; Lunsdorf, H.; Timmis, K.N.; Golyshin, P.N. Oleispira antarctica gen. nov., sp. nov., a novel hydrocarbonoclastic marine bacterium isolated from Antarctic coastal seawater. Int. J. Syst. Evol. Microbiol. 2003, 53, 779–785.

82. Humphry, D.R.; George, A.; Black, G.W.; Cummings, S.P. Flavobacterium frigidarium sp. nov., an aerobic, psychrophilic, xylanolytic and laminarinolytic bacterium from Antarctica. Int. J. Syst. Evol. 2001, 51, 1235–1243.
83. Gosink, J.; Herwig, R.; Staley, J. Octadecabacter arcticus gen. nov., sp. nov., and O. antarcticus, sp. nov., non-pigmented, psychrophilic gas vacuolate bacteria from polar sea ice and water. Syst. Appl. Microbiol. 1997, 20, 356–365.
84. Zhang, D.-C.; Busse, H.-J.; Liu, H.-C.; Zhou, Y.-G.; Schinner, F.; Margesin, R. Sphingomonas glacialis sp. nov., a psychrophilic bacterium isolated from alpine glacier cryoconite. Int. J. Syst. Evol. Microbiol. 2011, 61, 587–591.
85. Franzmann, P.; Stackebrandt, E.; Sanderson, K.; Volkman, J.; Cameron, D.; Stevenson, P.; McMeekin, T.; Burton, H. Halobacterium lacusprofundi sp. nov., a halophilic bacterium isolated from Deep Lake, Antarctica. Syst. Appl. Microbiol. 1988, 11, 20–27.
86. Bowman, J.P. Description of Cellulophaga algicola sp. nov., isolated from the surfaces of Antarctic algae. Int. J. Syst. Evol. Microbiol. 2000, 50, 1861–1868.
87. Shrivastava, P.; Kumar, R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi J. Biol. Sci. 2015, 22, 123–131.
88. Kasim, W.A.; Gaafar, R.M.; Abou-Ali, R.M.; Omar, M.N.; Hewait, H.M. Effect of biofilm-forming plant growth promoting rhizobacteria on salinity tolerance in barley. Ann. Agric. Sci. 2016, 61, 217–227.
89. Bacilio, M.; Moreno, M.; Bashan, Y. Mitigation of negative effects of progressive soil salinity gradients by application of humic acids and inoculation with Pseudomonas stutzeri in a salt-tolerant and a salt-susceptible pepper. Appl. Soil. Ecol. 2016, 107, 394–404.
90. Krishnamoorthy, R.; Kim, K.; Subramanian, P.; Senthilkumar, M.; Anandham, R.; Sa, T. Arbuscular mycorrhizal fungi and associated bacteria isolated from salt-affected soil enhance the tolerance of maize to salinity in coastal reclamation soil. Agric. Ecosyst. Environ. 2016, 231, 233–239.
91. Hayat, R.; Ali, S.; Amara, U.; Khalid, R.; Ahmed, I. Soil beneficial bacteria and their role in plant growth promotion: A review. Ann. Microbiol. 2010, 60, 579–598.
92. Egamberdiyeva, D. The effect of plant growth-promoting bacteria on growth and nutrient uptake of maize in two different soils. Appl. Soil Ecol. 2007, 36, 184–189.
93. Bai, J.; Yang, X.; Du, R.; Chen, Y.; Wang, S.; Qiu, R. Biosorption mechanisms involved in immobilization of soil Pb by Bacillus subtilis DBM in a multi-metal contaminated soil. J. Environ. Sci. 2014, 26, 2.
94. Khan, Z.; Rehman, A.; Hussain, S.Z.; Nisar, M.A.; Zulfiqar, S.; Shakoori, A.R. Cadmium resistance and uptake by bacterium, Salmonella enterica 43C, isolated from industrial effluent. Amb. Express

2016, 6, 54.

95. Zhou, W.; Zhang, H.O.; Ma, Y.; Zhou, J.; Zhang, Y. Bio-removal of cadmium by growing deep-sea bacterium Pseudoalteromonas sp. SCSE709-6. Extremophiles 2013, 17, 723–731.
96. Dai, S.; Chen, Q.; Jiang, M.; Wang, B.; Xie, Z.; Yu, N.; Zhou, Y.; Li, S.; Wang, L.; Hua, Y.; et al. Colonized extremophile Deinococcus radiodurans alleviates toxicity of cadmium and lead by suppressing heavy metal accumulation and improving antioxidant system in rice. Environ. Pollut. 2021, 284, 117127.
97. Santos, S.P.; Yang, Y.; Rosa, M.T.G.; Rodrigues, M.A.A.; De La Tour, C.B.; Sommer, S.; Teixeira, M.; Carrondo, M.A.; Cloetens, P.; Abreu, I.A.; et al. The interplay between Mn and Fe in Deinococcus radiodurans triggers cellular protection during paraquat-induced oxidative stress. Sci. Rep. 2019, 9, 17217.
98. Hobbie, S.E.; Grimm, N.B. Nature-based approaches to managing climate change impacts in cities. Philos. Trans. R. Soc. Lond. B Biol. Sci. 2020, 375, 20190124.
99. Martínez-Arias, C.; Witzell, J.; Solla, A.; Martin, J.A.; Rodríguez-Calcerrada, J. Beneficial and pathogenic plant-microbe interactions during flooding stress. Plant Cell Environ. 2022, 45, 2875–2897.
100. Waadt, R.; Hsu, P.K.; Schroeder, J.I. Abscisic acid and other plant hormones: Methods to visualize distribution and signaling. Bioessays 2015, 37, 1338–1349.
101. Wani, S.H.; Kumar, V.; Shriram, V.; Sah, S.K. Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. Crop J. 2016, 4, 162–176.
102. Meena, K.K.; Sorty, A.M.; Bitla, U.M.; Choudhary, K.; Gupta, P.; Pareek, A.; Singh, D.P.; Prabha, R.; Sahu, P.K.; Gupta, V.K.; et al. Abiotic stress responses and microbe-mediated mitigation in plants: The omics strategies. Front. Plant Sci. 2017, 8, 172.
103. Belimov, A.A.; Dodd, I.C.; Safronova, V.I.; Hontzeas, N.; Davies, W.J. Pseudomonas brassicacearum strain Am3 containing 1-aminocyclopropane-1-carboxylate deaminase can show both pathogenic and growth-promoting properties in its interaction with tomato. J. Exp. Bot. 2007, 58, 1485–1495.
104. Bhadrecha, P.; Singh, S.; Dwibedi, V. A plant’s major strength in the rhizosphere: The plant growth promoting rhizobacteria. Arch. Microbiol. 2023, 205, 165.
105. Egamberdieva, D.; Wirth, S.J.; Alqarawi, A.A.; Abd-Allah, E.F.; Hashem, A. Phytohormones and beneficial microbes: Essential components for plants to balance stress and fitness. Front. Microbiol. 2017, 8, 2104.
106. Abd Allah, E.F.; Alqarawi, A.A.; Hashem, A.; Radhakrishnan, R.; Al-Huqail, A.A.; Al-Otibi, F.O.N.; Malikk, J.A.; Alharbi, R.I.; Egamberdieva, D. The endophytic bacterium Bacillus subtilis (BERA 71)

improves salt tolerance in chickpea plants by regulating the plant defense mechanisms. J. Plant Interact. 2018, 13, 37–44.

107. Gamalero, E.; Glick, B.R. Bacterial modulation of plant ethylene levels. Plant Physiol. 2015, 169, 13–22.
108. Shahzad, R.; Khan, A.L.; Bilal, S.; Waqas, M.; Kang, S.M.; Lee, I.J. Inoculation of abscisic acid-producing endophytic bacteria enhances salinity stress tolerance in Oryza sativa. Environ. Exp. Bot. 2017, 136, 68–77.
109. Dekas, A.D.; Poretsky, R.S.; Orphan, V.J. Deep-sea archaea fix and share nitrogen in methane-consuming microbial consortia. Science 2009, 326, 422–426.
110. Kuan, K.B.; Othman, R.; Abdul Rahim, K.; Shamsuddin, Z.H. Plant growth promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilization of maize under greenhouse conditions. PLoS ONE 2016, 11, e0152478.
111. Hider, R.C.; Kong, X. Chemistry and biology of siderophores. Nat. Prod. Rep. 2010, 27, 637–657.
112. Goswami, D.; Thakker, J.N.; Dhandhukia, P.C.; Tejada, M.M. Portraying mechanics of plant growth promoting rhizobacteria (PGPR): A review. Cogent. Food Agric. 2016, 2, 1127500.
113. Wang, D.; Lv, S.; Jiang, P.; Li, Y. Roles regulation and agricultural application of plant phosphate transporters. Front. Plant Sci. 2017, 8, 817.
114. Oteino, N.; Lally, R.D.; Kiwanuka, S.; Lloyd, A.; Ryan, D.; Germaine, K.J.; Dowling, D.N. Plant growth promotion induced by phosphate solubilizing endophytic Pseudomonas isolates. Front. Microbiol. 2015, 6, 745.
115. Joe, M.M.; Devara, S.; Benson, A.; Sa, T. Isolation of phosphate solubilizing endophytic bacteria from Phyllanthus amarus Schum & Thonn: Evaluation of plant growth promotion and antioxidant activity under salt stress. J. Appl. Res. Med. Aromat. Plants 2016, 3, 71–77.
116. Singh, M.; Singh, D.; Gupta, A.; Pandey, K.D.; Singh, P.K.; Kumar, A. Plant growth promoting Rhizobacteria: Application in biofertilizers and biocontrol of phytopathogens. In PGPR Amelioration in Sustainable Agriculture; Woodhead Publishing: Sawston, UK, 2019; pp. 41–66.
117. Kumar, A.; Vandana, R.S.; Singh, M.; Pandey, K.D. Plant growth promoting rhizobacteria (PGPR). A promising approach for disease management. In Microbes and Environmental Management; Singh, J.S., Singh, D.P., Eds.; Studium Press: New Delhi, India, 2015; pp. 195–209.
118. Singh, M.; Kumar, A.; Singh, R.; Pandey, K.D. Endophytic bacteria: A new source of bioactive compounds. 3 Biotech 2017, 7, 315.
119. Tapias, D.R.; Galvan, A.M.; Diaz, S.P.; Obando, M.; Rivera, D.; Bonilla, R. Effect of inoculation with plant growth-promoting bacteria (PGPB) on amelioration of saline stress in maize (Zea mays). Appl. Soil Ecol. 2012, 61, 264–272.

120. Sharma, A.; Shankhdhar, D.; Shankhdhar, S.C. Enhancing grain iron content of rice by the application of plant growth promoting rhizobacteria. Plant Soil Environ. 2013, 59, 89–94.
121. Sen, S.; Chandrasekhar, C.N. Effect of PGPR on growth promotion of rice (Oryza sativa L.) under salt stress. Asian J. Plant Sci. Res. 2014, 4, 62–67.
122. Hey, S.J.; Byrne, E.; Halford, N.G. The interface between metabolic and stress signaling. Ann. Bot. 2010, 105, 197–203.
123. Matilla, M.A.; Krell, T. Plant growth promotion and biocontrol mediated by plant-associated bacteria. In Plant Microbiome: Stress Response. Microorganisms for Sustainability; Egamberdieva, D., Ahmad, P., Eds.; Springer: Singapore, 2018; Volume 5.
124. Souza, R.D.; Ambrosini, A.; Passaglia, L.M.P. Plant growth-promoting bacteria as inoculants in agricultural soils. Genet. Mol. Biol. 2015, 38, 401–419.
125. Pandey, V.; Ansari, M.W.; Tula, S.; Yadav, S.; Sahoo, R.K.; Shukla, N.; Bains, G.; Badal, S.; Chandra, S.; Gaur, A.K.; et al. Dose-dependent response of Trichoderma harzianum in improving drought tolerance in rice genotypes. Planta 2016, 243, 1251–1264.
126. Ortiz, N.; Armadaa, E.; Duque, E.; Roldanc, A.; Azcona, R. Contribution of arbuscular mycorrhizal fungi and/or bacteria to enhancing plant drought tolerance under natural soil conditions: Effectiveness of autochthonous or allochthonous strains. J. Plant Physiol. 2015, 174, 87–96.
127. El-Daim, I.A.A.; Bejai, S.; Meijer, J. Improved heat stress tolerance of wheat seedlings by bacterial seed treatment. Plant Soil 2014, 379, 337–350.
128. Lamichhane, J.R. Rising risks of late-spring frosts in a changing climate. Nat. Clim. Chang. 2021, 11, 554–555.
129. Pareek, A.; Sopory, S.K.; Bohnert, H.K.; Govindjee. Abiotic Stress Adaptation in Plants: Physiological, Molecular and Genomic Foundation; Springer: Dordrecht, The Netherlands, 2010; 526p.
130. Miura, K.; Furumoto, T. Cold signaling and cold response in plants. Int. J. Mol. Sci. 2013, 14, 5312–5337.
131. Nagarajan, S.; Nagarajan, S. Abiotic tolerance and crop improvement. In Abiotic Stress Adaptation in Plants; Pareek, A., Sopory, S.K., Bohnert, H., Gobindjee, A., Eds.; Springer: Amsterdam, The Netherlands, 2010; pp. 1–11.
132. Su, F.; Jacquard, C.; Villaume, S.; Michel, J.; Rabenoelina, F.; Clement, C.; Barka, E.A.; Dhondt-Cordelier, S.; Vaillant-Gaveau, N. Burkholderia phytofirmans PsJN reduces the impact of freezing temperatures on photosynthesis in Arabidopsis thaliana. Front. Plant Sci. 2015, 6, 810.
133. Mittler, R. Abiotic stress, the field environment, and stress combination. Trends Plant Sci. 2006, 11, 15–19.

134. Franken, P. The plant strengthening root endophyte Piriformospora indica: Potential application and the biology behind. Appl. Microbiol. Biotechnol. 2012, 96, 1455–1464.
135. Ahmad, P.; Hashem, A.; Abd-Allah, E.F.; Alqarawi, A.A.; John, R.; Egamberdieva, D.; Gucel, S. Role of Trichoderma harzianum in mitigating NaCl stress in Indian mustard (Brassica juncea L.) through antioxidative defense system. Front. Plant Sci. 2015, 6, 868.
136. Brotman, Y.; Landau, U.; Cuadros-Inostroza, A.; Takayuki, T.; Fernie, A.R.; Chet, I.; Viterbo, A.; Willmitzer, L. Trichoderma-plant root colonization: Escaping early plant defense responses and activation of the antioxidant machinery for saline stress tolerance. PLoS Pathog. 2013, 9, e1003221.
137. Chang, P.; Gerhardt, K.E.; Huang, X.D.; Yu, X.M.; Glick, B.R.; Gerwing, P.D.; Greenberg, B.M. Plant growth promoting bacteria facilitate the growth of barley and oats in salt impacted soil: Implications for phytoremediation of saline soils. Int. J. Phytoremediat. 2014, 16, 1133–1147.
138. Naveed, M.; Mitter, B.; Reichenauer, T.G.; Wieczorek, K.; Sessitsch, A. Increased drought stress resilience of maize through endophytic colonization by Burkholderia phytofirmans PsJN and Enterobacter sp. FD17. Environ. Exp. Bot. 2014, 97, 30–39.
139. Naveed, M.; Hussain, M.B.; Zahir, Z.A.; Mitter, B.; Sessitsch, A. Drought stress amelioration in wheat through inoculation with Burkholderia phytofirmans strain PsJN. Plant Growth Regul. 2014, 73, 121–131.
140. Pinedo, I.; Ledger, T.; Greve, M.; Poupin, M.J. Burkholderia phytofirmans PsJN induces long-term metabolic and transcriptional changes involved in Arabidopsis thaliana salt tolerance. Front. Plant Sci. 2015, 6, 466.

Retrieved from https://encyclopedia.pub/entry/history/show/125734