**Plant Growth-Promoting Rhizobacteria Interactions Provide a Broad Spectrum for Ameliorating Plant Growth and Tolerating Environmental Stresses**

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**Abstract**

Drought, salinity, and temperature are the leading impediments to crop productivity and sustainability, and these factors are likely to get worse soon. A handful of adaptive approaches are indispensable and can alleviate numerous abiotic stresses. Plant-microbe collaborations serve as a capable mechanism to overcome these constraints. They meddle with the plant's physiological and biochemical activities at the gene level. Plant growth-promoting rhizobacteria (PGPR) in the rhizosphere are beneficial for the host plant. They may invigorate the crop directly or indirectly. PGPRs mitigate physical stresses by manufacturing 1-aminocyclopropane-1-carboxyl acid (ACC) deaminase, exopolysaccharides, cytokinins, gibberellins, auxins, osmolytes (as shown in figure 2), and antioxidants (such as superoxide dismutase and catalase). Furthermore, the PGPRs principally endorse biological nitrogen fixation and nutrient uptake (for instance phosphorus, potassium, nitrogen, and zinc) in field crops. This PGPRs also boost plant growth consequently building up its economic yield. In the current review, we emphasize the progressive outcome of PGPR’s on the growth of the plant and producing tolerance against physical stresses.

**Introduction**

In this era, our globe is facing challenges that require consideration to produce adequate foodstuff in a tenable manner in this population explosion and limited food resources. Numerous epiphytic and endophytic microorganisms have colonized the phyllosphere and rhizosphere of the plant, and they have the ability to form wavering acquaintance with their host plant. Generally, plant-microbial interactions exist in a profuse contrasting manner, and on profuse distinct degrees are unnoticeable to the naked eye. Fundamentally, all plant organs interact with microorganisms at a specific age of life. However, the synergies between plants and microbes can be favorable, impartial, or noxious which directly encourages the development, growth, and plant health(Newton et al., 2010). PGPR is a bacterial which boosts the economic produce and crop growth by inhabiting the roots (Wu et al., 2005). Several strains of the genus, Azospirillum, Arthrobacter, Bacillus, Azotobacter, Burkholderia, Pseudomonas, Enterobacter, Serratia, and Klebsiella were described to possess PGPR features (Saharan and Nehra, 2011). Besides, plant growth-promoting rhizobacteria (PGPR) can yield a combination of volatile substances, miscellaneous among bacterial species. PGPRs, or plant-allied microbes, have been found to benefit plants by producing IAA and ACC deaminases, ameliorating the intake of nutrients from the surroundings, and solubilizing phosphate. These actions are responsible for the augmentation in the roots and shoots development. Hence the prerequisite is to compose the approaches that can lessen the damage in the productivity of crops under unfavorable settings. Bacillus velezensis HNH9 and Bacillus altitudinis HNH7 PGPRs enhance the crop development by increasing the expression of genes connected with plant growth i.e., ARF1, EXP6, ARF18, CKX6, GID1b, and IAA9 (Hasan et al., 2022). Bacillus thuringiensis CHGP12 is a potential PGPR with enhanced opposed and growth-increasing capability against Fusarium wilt (Fatima et al., 2022). Moreover, profiteering of soil microbes of new plants or plant-microbe consolidations may overwhelm contradictory environmental factors, and plants that are created by beneficial symbiotic relationships are more heat and drought-tolerant and can more appropriately handle nutrient fertilizers. Many physicochemical approaches have been endorsed by scientists to elevate drought stress endurance among crop plants. These comprise some agronomic approaches like deep tillage, bed planting, and mulching, foliar dosing of glycone betaine osmolytes, phytohormones and proline. However, all these techniques are expensive, vigorous, and also labor exhaustive. In this review, we will highlight current research on how a symbiotic relationship between PGPR and plants is established. This review will highlight the advantages of PGPR usage over other crop improvement and protection approaches. The information will provide a guideline for advancement in agricultural practices, and it will assist in comprehending how the environment influences microbial community activity and plant diversity.
Utilization of rhizosphere competent pseudomonas indoloxydans (F3-47) for the stimulation and enhancement of growth in plants

Because of urbanization and unselective cutting of trees the acreage for crop sowing is swiftly lessening, occasioning food deficiency. With the intention of accomplishing the rising requirement by the elevating worldwide population, substitute approaches to enhance food productivity are being searched for. The practice of uninhibited usage of pesticides and fertilizers nevertheless elevates the production and checks the pests and insects, harmful downsides with these materials by the unceasing usage lessens the fertility of land, bereavement of the habitual microflora, infectivity of the ground water bodies and soil erosion. To prevent these constraints, researchers are redirecting their focus on the feasible approaches of plant protection (Huang et al., 2011). Crop growth enhancement with favorable microorganisms is a biodegradable approach to enhance crop productivity and control outbursts of infective bacteria (Cal et al., 2009) that operate either indirectly or directly. Direct enhancement is via nitrogen fixation, generation of auxins for instance indole acetic acid (IAA), cytokinins and gibberellins (as shown in figure 2) (Patten and Glick, 2002) and phosphates solubilization (Richardson, 2001). Indirect enhancement is via sequestration of Fe3+ by synthesizing siderophores, and cyanides that combat against the plant pathogenic organisms. Forms of the *Bacillus*, *Azospirillum*, *Actinobacter*, *Azotobacter*, *Bradyrhizobium*, and *Pseudomonas* genera are being extensively deployed as biodegradable fertilizers (Vessey, 2003). Amongst these, the *Pseudomonas* genus is well researched because of its valuableness as a growth enhancing and biocontrol representative in crop plants with comprehensive advantageous attributes. These types have been established to employ a hostile function by generating various antibiotic substances (Jenni et al., 1989; Wackett, 2000 ). Furthermore, they also generate phosphate, ammonia, and siderophores, and chemicals which can decompose cell wall. Because of these resourceful means of functioning the application of PGPR in the domain of biocontrol and biofertilization and has turned out to be imperative.

**ACC deaminase mediated salt tolerance as a corollary of plant-microbe synergy**

Conferring the Food and Agricultural Organization, salt stress will abolish half of the cultivable lands all over the world by 2050 (FAO, 2017). NaCl is the primary reason for augmented soil salinity that results in osmotic stress, which condenses the production of the plant because of intervention with various biochemical and physiological activities (Parida and Das, 2005). In plants, extraordinary concentrations of NaCl source a disproportion in K+ and Ca2+ uptake, impeding of protein synthesis, suppression of enzymes, diminished respiration and photosynthesis rates, early maturity in leaves, loss of cellular probity, and escalated reactive oxygen species (ROS) synthesis (Munns, 2002; Jha and Subramanian, 2014). High intensities of ROS are exceedingly vicious to plants owing to salinity, bringing about protein and DNA impairment by disrupting lipids in the cellular membrane (Basu et al., 2010). The plant generates numerous ROS foraging antioxidant enzymes to sustain ROS equilibrium for instance superoxide dismutase (SOD) and catalase (CAT) (as shown in figure 2) (Han and Lee, 2005), although an osmolyte proline upholds the plants against elevated osmotic stress (Upadhayay et al., 2011). Further, elevated salt levels increase ethylene (known as stress ethylene) production too, which is unfavorable for the plants. Salinity stress coupled with augmented production of ethylene impedes plant growth (Glick, 2005). It is the need of the hour to lessen ROS levels and ethylene synthesis to compensate for the plant loss without causing detriment to the advantageous ethylene. Furthermore, in crop plants, the proliferating osmolyte production for sustainably improving the growth and guarding them against saline conditions is indispensable too.

Some microorganisms, particularly bacteria, manufacture enzyme 1-amino-cyclopropane-1-carboxylic acid (ACC) deaminase under such contexts, which possess the potential to vitiate ACC (precursor of ethylene) and lessen the escalated synthesis of ethylene in salt-stressed environments (as shown in figure 2) (Glick 2005, 2013). Plant growth-promoting rhizobacteria (PGPR) that synthesize ACC deaminase enzymes can smooth plant health by either direct or indirect means (Glick, 2005). PGPR can either synthesize growth-stimulating substances, directly expediting nutrient procurement and development of the plant, or guard plants against plant pathogen-producing impeding substances indirectly (Liu et al., 1995 a, b; Carteaux et al., 2003). Additionally, in plants, few PGPR also produces cation (like Na+) binding exopolysaccharides in large quantity (Upadhayay et al., 2011), ultimately delivering salinity tolerance to plants by declining the concentration of available Na+. PGPRs may build up numerous ROS-prowling enzymes for instance CAT and SOD, assist to lower the increased levels of ROS in plants, and guard them against the harmful salinity consequences (Han and Lee, 2005). *Pseudomonas*, *Achromobacter*, *Arthrobacter*, *Ochrobactrum*, *Bacillus*, *Stenotrophomonas*, *Enterobacter*, *Serratia*, *Chryseobacterium*, and *Bacillus* are acknowledged as PGPR which produces ACC deaminase which defends the crops against salinity hazard (Upadhayay et al., 2011; Sarkar et al., 2018).

**Utility of rhizobacteria in enhancing salinity and drought endurance**

The output of agriculture is unquestionably influenced by physical stresses like drought and salinity across the globe. Accordingly, advancement of viable approaches that aid in outdoing plants...
tolerance against such stresses is crucial. A glut of soil microbes collaborating with plants influences plant growth and viability in the natural environment. To analyze the precision of such synergies between microorganisms and the host plant inclusive research has been administered (Berendsen et al., 2012, Averill et al., 2014). A category of microbes that have been cited to elevate the yield and growth is described in crop plants as growth-promoting rhizobacteria (PGPR). PGPR may be a biofertilizer or regulator and is broadly used in many crops with the aim of growth and protection against various unfavorable circumstances (Barnawal et al., 2012; Nadeem et al., 2014).

Nutrient uptake is escalated by several processes for instance biological nitrogen fixation, solubilization of phosphate, generation of siderophore, and rest is involved in lifting plant growth. Furthermore, modulation of plant hormone status is a dynamic feature of PGPR which boost plant toughness under unfavorable circumstances. Production of auxins and cytokinins through PGPR modifies plant hormone status (Dodd et al., 2010) or through lessening ethylene intensities in the plant (as shown in figure 1 and 2) via bacterial enzyme ACC deaminase (as shown in figure 1), which disintegrates the ACC to ammonia and α-ketobutyrate (as shown in figure 1) (Glick et al., 1998). Different rhizobacteria comprising ACC deaminase enzyme have exhibited to boost plant development during physical stresses which trigger ethylene production during stress (Mayak et al., 2004 a, b; Belimov et al., 2009).

Multifaceted effects of PGPR on plants are acknowledged (Jiang et al., 2012). Provision of nutrient source/sink shifts and intrusion of development and growth is done by plant hormones to abet plant numerous environmental conditions. (Peleg and Blumwald, 2011). Advantageous microbes possess the strength to mold hormonal balance in the plant for its safeguard during stressful circumstances (Planchamp et al., 2015). Modification of root-to-shoot signaling and concentration of shoot hormone by beneficial microbes strikes plant hormone crosstalk which enhances physiological processes in plants, development, and advancement during problems of drought and salinity (Dodd et al., 2010)

**Function of PGPR in the upsurge of drought endurance in plants**

There is a spacious assortment of environmental factors which affect plants. The major abiotic factors which influence the plant are flooding, cold, salinity, toxic metals, drought, and heat (Mishra et al., 2014). Amid these, water scarcity is the paramount factor that hinders crop production (Naveed et al., 2014). Probably, this stress impedes standard functions and alters the turgor and water potential of the crop, directing to amendments in plant morphological and physiological characteristics (Vurukonda et al., 2016). Drought persuades numerous physiological, morphological, and biochemical elements, such as lessening the leaf space and quanta of chlorophyll, reactive oxygen species production, and expanding the size of roots (Lata et al., 2011). Conventional engineering and plant breeding have been exploited to mend plant tolerance against drought. Production of drought-tolerant types via genetic engineering is problematic considering drought tolerance traits as a composite and multigenic one (Nautiyal et al., 2013). To commence on this, exercising drought-bearing plant growth-promoting rhizobacteria (PGPR) strains in a drought environment is a substitute measure for the tenable growth of the plant. PGPRs are acknowledged to boost the uptake of nutrients and expedite the crop growth either indirectly or directly. The PGPRs-mediated plant growth exaltation predominantly includes catering iron, phosphorus, nitrogen, potassium, and zinc as nutrients, and phytohormones manufacturing (Jha et al., 2012). PGPRs are fitted to a wide range of environments. PGPRs are proclaimed to alter the reactions at the gene level and subsequently facilitate plants to endure physical stresses (Srivastava et al., 2008). For reinforcing and restoring environmental sustainability, indigenous drought tolerant PGPRs may carry more competency. PGPR strains possess the notable capability for adjusting plant physiological response to water stress (Kaushal and Wani, 2016). PGPRs have been described to mitigate the dilemma of drought in several crops, for instance, chickpea, wheat, maize, pepper, tomato, and pea (Sandhya et al., 2010; Naveed et al., 2014; Tiwari et al., 2016).

**Developing endurance against drought stress by inoculating growth-promoting rhizobacteria in plants**

Crop plants in semi-arid and arid areas come encounter various abiotic constrains when cultivated in including water scarcity, salinity stress, and elevated temperature (Liu et al., 2020). Together with all these forms of problems, the most rigorous and harmful issue in the entire globe is scarcity in water availability. It has been projected that water shortage problem would bring about nearly about 50 percent shortfall in crop productivity, particularly in the semi-arid and arid zones by 2050. Drought affected crop generally encounters water deficit together with reduced proficiency of nutrient uptake, reduced photosynthesis, disruption in hormonal balance, and elevated synthesis of reactive oxygen species (ROS) (Getnet et al., 2015; Siddiqi and Husen 2017, 2019). To combat the drought constraint, plants generate osmoprotectants and antioxidants that slows them down in surviving the stressful environments. Stress comprises hormone imbalance, and disruption causes the elevated production of abscisic acid, trivial lessening in the amounts of gibberellins and indole acetic acid accompanied by an abrupt reduction in the zeatin concentration in the leaves. The endogenic concentration of cytokines diminishes with an enhance in water deficit stress, occasioning enhanced concentrations ethylene in the roots. Serval microbes
inhibit the roots area of plants, denoted as rhizosphere that comprises a diversified biological population, affecting plant growth and production because of their numerous metabolic functions and interfaces with the plants (Berg, 2009; Schmidt et al., 2014). In the locality of roots, physical modifications arise in bacterial populations linked with the plant that choose their grouping as an acclimatization toward physical stresses, facilitate in improving the endurance against stress to provide vigor and resistance from water deficit (Cherif et al., 2015; Sabir et al., 2020). At present, there are several approaches to alleviate the water scarcity problem, and these are chemical, physical, and biological methods. Numerous physiochemical appearances have been endorsed by scientists to elevate drought endurance in plants. Additionally, biological strategies would prove economical and proficient.

**Categorization of plant growth-promoting rhizobacteria and their application as bio control agent**

The rhizosphere focuses on plants that may harbor miniaturized scale biota which is accounted for to adjust the reaction of host plants to environmental pressures. A few instruments have been anticipated through which rhizobacteria can advance plant development, together with phytohormone generation, nitrogen fixation, improving stress endurance, and expanding the accessibility or number of essential supplements to the host plant (as shown in figure 2) (Wu et al., 2005) and blend of proteins and fungicidal mixes (Ahmad et al., 2008). They likewise assume a momentous job in plant reactions to physical and non-physical stresses. Numerous microbes are prepared to do creating more than one sort of plant hormone, in this manner influencing the host plant physiology by a few different means (Boiero et al., 2007). An Earth-wide temperature boost under an evolving climate will represent a noteworthy imperative to edit generation due to adjustments in the physiologic of the plant that in this way influence the plant-microorganism communications. Living beings react to unexpected temperature increments by inciting the combination of explicit polypeptides, called warmth stun proteins (HSP). A thermo-tolerant Pseudomonas (as shown in table 1) aeruginosa strain, AMK-P6, segregated from a semi-bone-dry district revealed the acceptance of HSP once uncovered to elevated temperature (Ali et al., 2009).

**Convergent expansion and contraction of genomic islands make lifestyle modifications in plant-linked pseudomonas**

Circumstances of bacterial existence on host robustness due to adaptation to host diverges from commensal (neutral effect) to mutualistic (positive effect) and to pathogenic (negative effects) (Hirsch et al., 2004). Numerous adjacent bonds which are produced by co-evolution establish an intricate communication between host and bacteria (Xin et al., 2018; Jones et al., 2007). Via the acquirement and deprivation of virulence gene the horizontal gene transfer (HGT) will initiate swift existence evolutions in host-allied bacteria (Savory et al., 2017; Lin and Koskella, 2015). Taking the example of E.coli development from commensal heredities in which loss and procurement of pathogenicity play a crucial role. (Tenaillon et al., 2010). Correspondingly, lucrative plant associated Rhodococcus strain is transformed into pathogens by virulence plasmid, and strains deprived of it revert to commensalism (Savory et al., 2017). It still has to be comprehended whether procurement of pathogenicity genes vitalities genomic feather loss affiliated with commensalism. Pseudomonas fluorescents species (Pfi) complex possessing both beneficial pathogenic strains are additionally used to observe in what way existing lifestyle alterations in plant-allied bacteria influence genome evolution (Quibod et al., 2015; Belimov et al., 2007). In multifarious plants including Arabidopsis thaliana, in adjacent proximity of plants root (the rhizosphere) Pfi strains are supplemented pertaining to neighboring soil (Bulgarelli et al., 2012; Lundberg et al., 2012). Lucrative effects on the health of Arabidopsis thaliana like enhancement in protection against pathogens, formation of a lateral root, and plant insusceptibility adjustment are by single Pfi strains (Haney et al., 2018), while disorders such as rice sheath rot (Kim et al., 2015) and tomato pith necrosis (Scarlett et al., 1978) are caused by other strains. Consequently, the Arabidopsis-associated complex of Pfi species is utilized to comprehend in what way strains transit alongside the symbiosis range from beneficial to pathogenic and by what means that may influence genome evolution.

**Improving plant production by applying microbes**

Adopting beneficial microbes, like fungi and bacteria, affiliated with the plant roots proposes contemporary solutions adding to crop production (Nadeem et al., 2014; Hanin et al., 2016). Bacteria inhabiting the rhizosphere (small region neighboring the plant roots) having the ability to increase stress resistance and crop growth are described as growth-promoting rhizobacteria in plants (Zelicourt et al., 2013). They possess the ability to boost stress resistance and crop growth via numerous indirect or direct workings (Glick et al., 2012; Kaushal and Wani 2016; Timmusk et al., 2017). PGPRs can generate growth regulators, and hormones, and harmonize their concentrations in crop plants, comprising salicylic acid, indole acetic acid, auxins, ethylene, gibberellic and absicic acids (Ahmed and Hasnain., 2014). Furthermore, PGPR serves as a bio-fertilizer two, broadening procurement by solubilization of distant nutrients and improving availability of the nutrient such as phosphate (Khan et al., 2013), solubilization of minerals through the provision of chelators (Palhares et al., 2015) and nitrogen fixation (Ardley, 2017; Sankhla et al., 2017). Moreover, it has been noted that PGPR is potent in many physiological and metabolic mechanisms thereby, controlling the
precarious outcomes of various stresses for instance pesticide resistance (Duby and Fulekar., 2013; Jones and Edwards., 2016), and remedying toxic metals (Liu et al., 2015; Karthik et al., 2017; Oves et al., 2017) and resistance to shortage of water and salinity (Daffonchio et al., 2015; Mahmood et al., 2016). PGPR surrogates traditional methods for soil remediation affected with metals which keep up the fertility of the land and elevate crop growth (Khan et al., 2009b). Not only, pseudomonas demote the uptake of chromium but also augment the biochemical traits of the plant grown on soil manipulated with chromium (Oves et al., 2013). Understanding the PGPR’s role in boosting functional growth, especially about PGP activities, such as intensification of yield and plant growth needs uninterrupted efforts to recognize and distinguish novel PGPR in the field environment (Khan et al., 2009a). Nevertheless, the plant-microorganism synergies can be fluctuating by alterations in soil physicochemical attributes, modification mechanisms, ecological surroundings, and bacterial haleness and host reactions and are complicated (You et al., 2016; Zhou et al., 2016; Eida et al., 2017).

### Advancement in nitrogen fixation and nitrogen remobilization and vegetative growth by inoculating rhizobacteria

An escalation in plant yield and growth and with concurrent diminishing use of chemical fertilizer is noticed when Plant growth-promoting rhizobacteria (PGPR) segregated as soil bacterium from the rhizosphere in consortium with roots and supplementary parts of the crop plant (Lugtenberg and Kamilova, 2009). Via biological nitrogen fixation (BNF), phytohormone synthesis (such as gibberellin, auxin, and cytokinin as shown in figure 2), solubilization of phosphate, and control of soil pathogens biologically. Several bacteria for instance Azospirillum (Montanez et al., 2009), Burkholderia (Chelius et al., 2001). Pseudomonas (Pironyou et al., 2011), and Bacillus (Zakry et al., 2012) have been recognized as PGPR (as shown in table 1 and 2). It is currently discovered that about 12-70 percent of overall N uptake in crop plants is contributed by PGPR or 26.7 kg N per hectare i.e., 70% of overall uptake of N in maize (Montanez et al., 2009), and oil palm (Zakry et al., 2012). Generally, BNF is a progressively vital module in upcoming plant-N regulation, according to evaluation it subsidizes up to 65% of N utilized in agriculture (Matiru and Dakora, 2004). Furthermore, to reuse the N from non-reproductive plant portions for growing organs exclusively seeds grains N remobilization in the plant has a pivotal role. The principal stimulus of N remobilization is leaf senescence which happens naturally every time the plant needs it and during plant growth (Uharte and Andrade, 1995). Remobilization of N from the leaf is reported to be 50–90% in wheat and maize grains (Kichey et al., 2007). For efficacious plant-N management, a concerted effort is required. Therefore, PGPR strains are chosen constructively from a succession of native bacterium forms via biochemical categorizations and advancement of plant growth assessments. 16S rDNA gene evaluation is done to recognize selected and reference strain UPMB10. The 15N isotope dilution method is used to study their impact on plant-N remobilization before flowering and harvesting of the ear.

### Table 1. Position of PGPR in enhancing stress tolerance in plants

<table>
<thead>
<tr>
<th>Microbes</th>
<th>Plant specie</th>
<th>Function</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azospirillum</td>
<td>Zea mays (Maize)</td>
<td>Generate biocidal substance and tolerance to abiotic stress.</td>
<td>(Creus et al., 2010; Vacheron et al., 2015)</td>
</tr>
<tr>
<td>Paenibacillus</td>
<td>Ciser arietinum (Chickpea)</td>
<td>Known to promote growth via nitrogen fixation</td>
<td>Yolcu et al., (2011)</td>
</tr>
<tr>
<td>B.japonicum</td>
<td>Glycine max (Soyabeen)</td>
<td>Helps in providing drought resistance to soyabeen.</td>
<td>(Hasanah and Rahmawati, 2012)</td>
</tr>
<tr>
<td>Bradyrhizobium</td>
<td>Vigna unguiculata (Cowpea)</td>
<td>Tolerance of cow pea plant to scarcity stress.</td>
<td>(Hasanah and Rahmawati, 2012)</td>
</tr>
<tr>
<td>Azospirillum brasiliens</td>
<td>Oximum basilicum L. (Sweet Basil)</td>
<td>Improve chlorophyll pigment content and oxidant activity under water stress.</td>
<td>(Heidari and golpayegani, 2012)</td>
</tr>
<tr>
<td>Pseudomonas fluorescens</td>
<td>Oryza sativa (Rice)</td>
<td>Intrinsic tolerance of rice plant to drought stress. Encourage expression of abscisic acid.</td>
<td>(Saakre et al., 2017)</td>
</tr>
<tr>
<td>Rhizobium leguminosarum</td>
<td>Vicia faba (Faba bean)</td>
<td>Increase number of nodule formation, Promote Faba bean productivity and resistance to alkalinity stress.</td>
<td>Abd-Alla et al., (2014)</td>
</tr>
<tr>
<td>Pantoea</td>
<td>Saccharum officinarum (Sugarcane)</td>
<td>Endophytic nitrogen fixation in sugarcane</td>
<td>Singh et al., ( 2021)</td>
</tr>
<tr>
<td>Bacillus amylolique faciens</td>
<td>Zea mays (Maize)</td>
<td>Contribute to maize tolerance by enhancing its chlorophyll production level by interacting with roots.</td>
<td>Chen et al., (2016)</td>
</tr>
</tbody>
</table>
### Table 2. Manipulation of genes by PGPR for stress resistance

<table>
<thead>
<tr>
<th>PGPR</th>
<th>Plant</th>
<th>Genes Regulated By PGPR</th>
<th>Function</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBS (B. cereus AR156, B. subtilis SM221 and Serratia sp. XY21)</td>
<td>Cucumis sativus (Cucumber)</td>
<td>cAPX, rbcL, rbcS</td>
<td>Enhance superoxide dismutase (SOD) activity and mitigate the drought triggered down-regulation of expression of the genes</td>
<td>(Wang et al., 2012)</td>
</tr>
<tr>
<td><em>Pseudomonas simiae</em></td>
<td>Glycine max (Soybean)</td>
<td>DB/EREB</td>
<td>Enhance production of abscisic acid and reduction of ethylene emission associated with promoting drought tolerance</td>
<td>(Lim and Kim, 2013)</td>
</tr>
<tr>
<td><em>Dietzia natronolimnaea</em></td>
<td>Triticum aestivum (Wheat)</td>
<td>SOS 1, SOS 4, TaST</td>
<td>Protecting salt stress by modulating transcriptional machinery responsible for salinity tolerance</td>
<td>(Bharti et al., 2016)</td>
</tr>
<tr>
<td><em>Bacillus amyloliquefaciens</em></td>
<td>Arabidopsis thaliana</td>
<td>CYCD4-1, CNP (Crooked neck protein)</td>
<td>Induces systematic salt tolerance, enhances fresh and dry weight</td>
<td>(Liu et al., 2017)</td>
</tr>
<tr>
<td><em>Glucanacetobacter diazotrophicus</em> PAL 5</td>
<td>Saccharum officinarum (Sugar cane)</td>
<td>ABA-dependent signaling genes</td>
<td>Confer drought tolerance</td>
<td>(Vurukanda et al., 2016)</td>
</tr>
</tbody>
</table>

### Diagram 1

Diagram 1 illustrates the molecular mechanisms underlying the interaction between PGPR and plants under stress conditions. The diagram highlights the role of enzymes like ACC (Aminocyclopropane-1-carboxylate) and the production of ethylene, which are key factors in plant response to stress. The diagram also marks the presence of specific genes and enzymes, such as AcdR, Lip, and FNR, which play crucial roles in the metabolic pathways under stress conditions.
Description: The regulation of ACC deaminase gene: the DNA sequence for the upstream of acdS gene contains a cyclic AMP receptor protein binding site (CRP), fumarate-nitrate reduction regulatory protein-binding site (FNR) and Leucine-responsive regulatory protein (LRP). The role of ACC deaminase in inhibiting the production of ethylene and its comparison with the mechanism in normal condition.

Diagram 2

Description: Role of PGPRs in mitigating the effects of drought stress: PGPRs stimulate the secretion of osmolytes and phytohormones which improve the water retention in leaves and water absorption.

Conclusion And Future Prospects

Environmental constraints are powerful hindrances to crop productivity. PGPR has an imperative part in providing adaptation and endurance to plants in stressful surroundings and can also play the prospective function in resolving food security problems of the future. The synergy between rhizobacteria and plant affects and improves plant growth by providing tolerance against stresses. Although it is possible to create stress-tolerant plant varieties through plant breeding and genetic manipulation, this process can be difficult and time-consuming because many tolerance traits are polygenic and complex, whereas application of PGPR in plants to mitigate stress reveals a novel chapter of microbial inoculation in arid land agriculture. The fluctuations provoked by PGPR such as generating novel genes and stimulating various enzymes play a considerable part in endorsing plant survival during stress. If we focus toward the creation of stress-resistant cultivars, it will be time consuming to produce a novel line, that will exhibit tolerance. In contrast, there is a substitute to these time-taking and costly methods that a minute entity in the soil can accomplish this in a brief time duration and even more inexpensively. So, in future, the application of an eco-friendly method that comprises the inoculation of PGPR may be realized workable and proficient. The PGPRs may add success to restoring and enhancing crop productivity and agricultural sustainability in the times to come. Considering the present situation, well-focused and resolute future research is required in determining reliable microbial strains and assessing the prospective organisms.

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