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RESEARCH ARTICLE

IMPACT OF PGPR ON THE SUSTAINABLE DEVELOPMENT OF AGRICULTURE: CURRENT AND FUTURE PROSPECTS

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Abstract

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The quest for boosting agricultural yields due to increased stress on food production has inevitably brought about the indiscriminate use of chemical fertilizers and different agrochemicals. Biofertilizers facilitate the overall growth and yield of crops in an eco-friendly manner. They comprise residing or dormant microbes implemented in the soil or used for treating crop seeds. One of the most applicants in this respect is rhizobacteria. Plant growth-promoting rhizobacteria (PGPR) are an important group of beneficial, root-colonizing bacteria. They exhibit harmonious and divergent interactions with the soil microbiota and interact in an array of activities of ecological meaning. They encourage plant growth by facilitating biotic and abiotic stress tolerance and aid the nutrition of host plants. Due to their lively growth endorsing activities, PGPRs are considered an eco-friendly alternative to dangerous chemical fertilizers. Chemical fertilizers used in agriculture to improve yields and eradicate pathogens, however, negatively influence the ecosystem. The doubts over pesticide side effects, there is a growing interest in better thoughtfulhelpful interactions between plants and rhizosphere microbial populations. As a result, biological agents are in high demand around the world. The use of plant growth-promoting Rhizobacteria (PGPR). They have a crucial function in increasing soil fertility, promoting plant growth, and suppressing phytopathogens for the development of environmentally friendly sustainable agriculture.In this section, we try to devise a strategy for increasing crop output and health, developing sustainable agriculture, and commercialization through the use of plant growth-promoting rhizobacteria.

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Introduction:-

At present cultivation techniquesundifferentiatingthe use of fertilizers, especially nitrogenous and phosphorus, have brought about significant environmental pollution. Extreme use of these chemical compounds employsharmful outcomes on soil microorganisms, and affects the overall fertility status of soil(Youssef et al., 2014). The usefulness of these fertilizers on a long-term foundation often results in a decrease in pH and transferable bases for that reason making them unavailable to plants and the use of crops declines. To understand the problem and avoid this

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difficultyfor better plant yields, farmers have relied on chemical reasserts of nitrogen and phosphorus. Besides, the production of chemical fertilizers reduces nonrenewable resources, the oil and natural gas used to produce these fertilizers, to tackle environmental hazards (Joshi et al., 2006; Savci, 2012;Dhankhar and Kumar, 2023).

Over the previous couple of decades, the agriculture procedure in India has set a goal through diversification and emphasis on a sustainable production system. Rhizosphere research established an exciting idea for research around plant roots called the rhizosphere. The term rhizosphere was introduced by Lorenz Hiltner in 1904 (Hartmann et al., 2008). The primaryimpactson rhizosphere microorganisms have on plants now turn out to be crucial tools to protect the health of plants in an eco-friendly manner (Avis et al.,2008). These microorganisms can affect plant growth frequently known as plant growth-promoting rhizobacteria (PGPR). These are relatedtomany biotic activities of the soil ecosystem to make it lively for nutrient turnoverultimately leadingto sustainable crop production (Kloepper et al., 1980; Khan et al., 2009; Bhardwaj et al., 2014).

In recent years PGPR is used to replace agrochemicals (fertilizers and pesticides) for plant growth promotion through various mechanisms that involve soil structure formation, decomposition of organic matter, recycling of crucial elements, solubilization of mineral nutrients, generating several plant growth regulators, stimulation of root growth, crucial for soil fertility, biocontrol of soil and seed borne plant pathogens and in promoting changes in vegetation (Arora et al., 2011; Sivasakhtiet al., 2014;Gupta et al., 2015; Karnwal et al., 2023).

Proficiencyin plant growth promoting rhizobacteria and their interactions with biotic and abiotic factors is important in bioremediation techniques, energy generation processes, and various biotechnological industries which include pharmaceuticals, food, chemical, and mining (Sagar et al., 2012; Gupta et al., 2015; Khan and Bano, 2016). Additionally, plant growth-promoting rhizobacteria can reduce chemical fertilizersand are environmentally beneficial for lower manufacturing costs as well as catch the best soil and crop management practices to obtain more supportable agriculture. (Kuffner et al., 2008; Iqbal et al., 2012; Maheshwari et al., 2012).

Plant growth promoting rhizobacterialforms:
Plant growth-promoting rhizobacterial comprises two forms that areExtracellular plant growth-promoting rhizobacteria (ePGPR) and intracellular plant growth-promoting rhizobacteria (iPGPR) (Martínez-Viveroset al.,2010).ePGPRs can be found in the rhizosphere, on the rhizoplane, or in the spaces between root cortex cells, whereas iPGPRs often occurs inside the specialized nodular structures of root cells (Ahmed and Kibret, 2014). ePGPR is found in bacterial genera such as Agrobacterium, Arthrobacter, Azotobacter, Azospirillum,Caulobacter, Chromo-bacterium, Erwinia, and Flavobacterium. The iPGPR is a member of the Rhizobiaceae family, which includes Allorhizobium, Bradyrhizobium, Mesorhizobium, Rhizobium, endophytes, and Frankia species, all these types symbiotically fix atmospheric nitrogen with higher plants (Bhattacharyya and Jha, 2012).

Plant Growth Promotion: Mode of Action
plant growth-promoting rhizobacteria is well-known for plant growth and promotion and, this growth improvement is due to certain traits of rhizobacteria. There are several mechanisms utilized by PGPR for enhancing plant growth and improvement in various environmental conditions. According to Kloepper and Schroth, 1981, Plant growth promoting rhizobacteria promotes plant growth through the production of numerous substances. In general, plant growth promoting rhizobacteria promote plant growth directly through eithernutrient supply (nitrogen, phosphorus, potassium, and essential minerals) or modulating levels of plant hormone, or indirectly by reducing the inhibitory outcomes of various pathogens on plant growth and development in the varieties of biocontrol agents, such asroot colonizers, and environmental protectors (Kloepper and Schroth, 1981; Vessey, 2003).

Direct mechanisms
Plant growth-promoting rhizobacteria follow the direct mechanisms that enable nutrient uptake processor likes, boom nutrient availability by nitrogen fixation, solubilization of mineral nutrients, mineralize natural compounds, and engineering of phytohormones (Adesemoye et al., 2009, Bhardwaj et al., 2014, Parewa et al., 2014).

Nitrogen fixation:
Nitrogen is an indispensableportion for all forms of life and it's far the most vital nutrient for plant growth and overall productivity. Though nitrogen covers 78 % of the atmosphere, it remains unavailable to the flora. Undesirably, no plant species is capable of fixing atmospheric dinitrogen into ammonia and droppingdirectly for its growth and development. Consequently, the atmospheric nitrogen is converted into plant-utilizable forms over

biological nitrogen fixation (BNF) which changes nitrogen to ammonia through nitrogen-fixing microorganisms using a complex enzyme system called nitrogenase (Gaby and Buckley, 2012).

PGPRcan fix atmospheric nitrogen and offer it to plants by two mechanisms: symbiotic and non-symbiotic. Symbiotic nitrogen fixation is an example of a mutualistic relationship between a microbe and a plant. Rhizobia are anextensive organization of rhizobacteria that are capable to perform symbiotic interactions through thecolonization and formation of root nodules with leguminous plants, in which nitrogen is fixed to ammonia making it available for the plant (Zeng et al., 2022). The plant growth-promoting rhizobacteria broadly offered as symbionts are Rhizobium, Bradyrhizobium, Sinorhizobium, and Mesorhizobium with leguminous plants, Frankia with non-leguminous trees and shrubs (Zahran, 2001; Zeng et al., 2022). On the other hand, non-symbiotic nitrogen fixation is carried out by free-dwelling diazotrophs and this will stimulate non-legume plant growth which includes radish and rice. Non-symbiotic Nitrogen fixing rhizosphericmicro-organismsappropriate to genera which include Azoarcus, Azotobacter, Acetobacter, Azospirillum, Burkholderia, Diazotrophicus, Enterobacter, Gluconacetobacter, Pseudomonas and cyanobacteria (Vessey, 2003; Bhattacharyya and Jha, 2012). The candidates' genes for nitrogen fixation, called (nif) genes are discovered in each symbiotic and free-living classification (Reed et al., 2011). Nitrogenase (nif) genes contain structural genes, involved in the activation of the Fe protein, iron-molybdenum cofactor biosynthesis, electron donation, and regulatory genes required for the synthesis and function of the enzyme. Inoculation through biological nitrogen-fixing plant growth-promoting rhizobacteria on cropsoffers an integrated method for growth-promoting activity, holding the nitrogen level in agricultural soil (Fani et al., 1992; Reed et al., 2011).

Phosphate solubilization:
Phosphorus is another nutrient of plants, subsequent to nitrogen (N). It plays a critical role in almostall-important metabolic processes in plants which includes photosynthesis, energy transfer, signal transduction, biosynthesis, and respiration (Khan et al., 2009).Plants are not able to utilize phosphate due to the fact 95-99% phosphate is present in the insoluble, immobilized, and precipitated form. Basically, Plants absorb phosphate most efficiently in two soluble forms, the monobasic (H_2PO_4) and the dibasic (HPO_4^{2-}) ions (Bhattacharyya and Jha, 2012). Plant growth-promoting rhizobacteria present in the soil usesdifferent techniques to make use of unavailable types of phosphorus to available forms for plants. The phosphate solubilization mechanisms working through plant growth-promoting rhizobacteria include the release of complexing or mineral-dissolving compounds liberation of extracellular enzymes (biochemical phosphate mineralization) and the release of phosphate during substrate degradation (biological phosphate mineralization) (Sharma et al., 2013). Examples of Phosphate solubilizing PGPR areincluded in the genera Enterobacter, Erwinia, Flavobacterium, Micro bacterium Pseudomonas Arthrobacter, Bacillus,Rhizobium,and Serratia have attracted the attention of agriculturists as soil inoculums to enhance plant growth and yield. Though, the beneficial outcomes of the inoculation with phosphate solubilizing bacteria used unaccompanied or in a mixture with different rhizospheric microbes have been also reported (Zaidi et al., 2009; Khan et al., 2009).

Potassium solubilization:
Potassium (K) is considered 1/3 major vital macronutrient for plant growth. The concentrations of soluble potassium in the soil are not fixed which may be very in the soil and exists in the form of insoluble rocks and silicate minerals (Parmar and Sindhu, 2013). Moreover, because of imbalanced fertilizer utility, potassium deficiency is considered one of the main limitations in crop production. In deficiency of potassium, the plants could have poorly developed roots, grow slowly, produce small seeds, and feature lower yields. This stressed the pursuit to find an alternative originalsupply of potassium for plant uptake and to maintain potassium status in soils for maintaining crop production (Pandey et al., 2020). PGPRis capable of solubilizing potassium rock through the production and secretion of organic acids (Han and Lee, 2006). Potassium solubilizing plant growth-promoting rhizobacteria such as Acidothiobacillusferrooxidans, Bacillus edaphicus, Bacillus mucilaginous, Burkholderia, Paenibacillus sp. and Pseudomonas has been mentioned to release potassium in accessible form from potassium-bearing minerals in soils (Singh et al., 2010; Liu et al., 2012; Gandhi et al., 2023). Consequently, the application of potassium solubilizing plant growth promoting rhizobacteria as biofertilizers for the development of agriculture can lessen the use of agrochemicals and assistance-friendly crop production.

Siderophore manufacturing:
Iron is a vital micronutrient for virtually all organisms in the biosphere. Iron is the fourth most abundant element on earth, in aerobic soils, however, iron is now no longer simply assimilated by either bacteria or plants because of ferric ion or Fe 3, which is the primary shape in nature, (Ma, 2005). Microorganisms have progressed specialized

mechanisms for the assimilation of iron, which includes the creation of low molecular weight iron-chelating compounds identified as siderophores, which transport this element into their cells (Schwyn and Neilands, 1987; Arora et al., 2013). In general, Siderophores are divided into 3 major families, i.e., hydroxamates, catecholates, and carboxylates. At present greater than 500 different kinds of siderophores are reported, among them, 270 were structurally characterized (Cornelis,2010). Siderophores were usedin both direct and indirect enhancement of plant growth by plant growth-promoting rhizobacteria. Examples of plant growth-promoting rhizobacteria such as Aeromonas, Azadirachta, Azotobacter, Bacillus, Burkholderia, Pseudomonas, Rhizobium, Serratia, and Streptomyces sp., and better chlorophyll levels in comparison to uninoculated flora (Sujatha, 2013; Sharma and Johri, 2003).

Phytohormone production

An extensive variety of microorganisms discovered within side the rhizosphere is capable of producing materials that regulate plant growth and development. Plant growth-promoting rhizobacteria produce phytohormones comprising auxins, cytokinins, gibberellins, and Ethylene that can regulate the overall development of plants. (Arora et al., 2013).

Among plant hormones, indole acetic acid (IAA) is the most common natural auxin present in plants, and it has a great impact on root growth (Miransari and Smith, 2014). It is asserted that up to 80% of rhizobacteria can synthesize indole acetic acid (IAA) colonized the seed or root surfaces is projected to behave in combination with endogenous IAA in plants to stimulate cell proliferation anduptake of minerals and nutrients from the soil (Vessey,2003). IAA impacts plant cell division, extension, and differentiation; stimulates seed and tuber germination; regulates the physiology of plants in order to maintain the overall, growth and development of plants (Spaepen and Vanderleyden, 2011). Tryptophan is an amino acid typically located in root exudates and has been identified as the most important precursor molecule for the biosynthesis of IAA in bacteria (Etesami et al., 2009). The biosynthesis of indole acetic acid through plant growth-promoting rhizobacteria comprisesthe formation of indole-3-pyruvic acid and indole-3-acetic aldehyde that is the common mechanism in bacteria like Pseudomonas, Rhizobium, Agrobacterium, Enterobacter and Klebsiella (Shilev, 2013). Furthermore, microbially produced phytohormones are more operativebecause,the inhibitory and stimulatory points of chemically produced hormones are low, on the contrary, microbial hormones are greater effective in terms ofnon-stop slow release.Several plant growths promoting rhizobacteria Azotobacter sp., Rhizobium sp. Rhodospirillumrubrum, Pseudomonas fluorescens, and Bacillus subtilis can produce cytokinins or gibberellins or both that can promote plant growth promotion (Kang et al., 2010).

Ethylene is a crucial phytohormone that has awidespreadimpact on biological activities that can have an effect on plant growth and development which includes promoting root initiation, inhibiting root elongation, promoting fruit ripening, promoting lower wilting, stimulating seed germination, promoting leaf abscission, activating the synthesis of different plant hormones (Glick et al., 2007). It is reported that the high concentration of ethylene induces defoliation and different cellular processes which could lead to decreased crop performance. The enzyme 1-aminocyclopropane-1 carboxylic acid (ACC) is a main for ethylene production, catalyzed through ACC oxidase (Iqbal et al., 2012). Currently, bacterial strains displaying ACC deaminase activity have been identified in a wide varietyof genera such as Acinetobacter, Achromobacter, Agrobacterium, Alcaligenes, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Ralstonia, Serratia and Rhizobium, etc. (Kang et al., 2010).

In-direct mechanisms

Phytopathogenic microorganisms are a majorelement for the frequentmenace to sustainable agriculture and ecosystem, which disrupt the environment, degrade soil fertility, and therefore showunsafe outcomes on human health. Indirectly, Plant boom selling rhizobacteria is a promising sustainable, and environmentally friendly method to gain sustainable fertility of the soil and plant boom. This method canencourage a huge variety of plant boom-selling rhizobacteria caused decreasing the need for agrochemicals (fertilizers and pesticides) to enhance soil fertility through othermechanisms via the manufacturing of antibiotics, siderophores, HCN, hydrolytic enzymes,etc. (Lugtenberg and Kamilova, 2009; Tariq et al., 2014).

Antibiotics:

The impact of antibiotic manufacturing is one of the most effective and studied biocontrol mechanisms of plant growth-promoting rhizobacteria towards (Shilev, 2013). Several antibiotics were known, which includes compounds such as amphisin, 2,4-diacetyl phloroglucinol (DAPG), oomycin A, phenazine, pyoluteorin, pyrrolnitrin, tropolone, and cyclic lipopeptides produced with the aid of using pseudomonads and oligomycin A, kanosamine, zwittermicin A, and xanthobaccin produced through Bacillus, Streptomyces, and Stenotrophomonas sp. to avoid the proliferation of plant pathogens(Compant et al., 2005; Loper and Gross, 2007). Many researchers have utilized biocontrol strains that synthesize one or more antibiotics (Glick, 2012). In soils, antibiotic 2, 4-diacetyl phloroglucinol (2, 4- DAPG) generating Pseudomonas sp. became suggested for biocontrol of disease in wheat caused by the fungus Gaeumanomycesgraminis var. tritici (de Souza et al., 2003). Bacterization of wheat seeds with P. fluorescens strains producing the antibiotic phenazine-1-carboxylic acid (PCA) utilized for approximately 60% of field trials (Weller, 2007). Bacillus amyloliquefaciens is known for lipopeptide and polyketide production for biological control activity and plant growth promotion activity against soil-borne pathogens (Ongena and Jacques, 2008). In addition to the manufacturing of antibiotics, some, rhizobacteria are also capable of producing unstable compounds referred to as hydrogen cyanide (HCN) for biocontrol of black root rot of tobacco, caused by Thielaviopsisbasicola(Voisardet al., 1994; Lanteigne et al., 2012).

Lytic enzymes:

Another interesting mechanism utilized by plant growth-promoting rhizobacteria. Basically, plant growth-promoting rhizobacterial traces can produce certain enzymes together with chitinases, dehydrogenase, β-glucanase, lipases, phosphatases, proteases,etc(Hayat et al., 2010; Joshi et al., 2012). With the aid of these enzymes, plant growth-promoting rhizobacteria play a very significant role, in particular, to protect them from biotic and abiotic stresses against pathogens which consist of Botrytis cinerea, Sclerotiumrolfsii, Fusariumoxysporum, Phytophthora sp., Rhizoctoniasolani, and Pythiumultimum (Upadhyay et al., 2012; Nadeem et al., 2013). A number of evidence have established the effectiveness of plant growth-promoting rhizobacteria as biocontrol agent which incorporates Pseudomonas fluorescens CHA0 suppress black root rot of tobacco introduced approximately via the fungus Thielaviopsisbasicola (Voisard et al., 1989). Pseudomonas putida in opposition to Macrophominaphaseolina in chickpea and Azotobacterchroococcumtowards Fusariumoxysporum in Sesamumindicumcorrespondingly in field condition (Maheshwari et al., 2012). Inoculation with Trichodermasp. has been the favored preference for novel biocontrol agents in opposition to Aspergillusniger the causal agent of collar rot of peanuts(Gajera et al., 2012). The use of multistrain inoculants is also an outstandingprocess that allows organisms to efficiently survive, and hold themselves in groups. Singh et al., 2013).

Siderophore:

Iron is a crucial growth cofactor for living organisms theavailability of solubilized ferric ions in soils is confined to neutral and alkaline pHfor the soil microorganisms, Siderophore-producing plant growth-promoting rhizobacteria can help the proliferation of pathogenic microorganisms by sequestering Fe^{3} within side the region around the root (Mehnaz et al., 2013). These siderophores bind with ferric ions and make siderophore ferricwhich binds with iron-limitation-established receptors on the bacterial cell surface. The Ferric ion is ultimately released and active in the cytoplasm as a ferrous ion. Numerous plants can use several bacterial siderophores as iron sources and low concentration promoted plant iron uptake. Several research documented theisolation of siderophore-generatingmicro-organisms belonging to the Bradyrhizobium, Pseudomonas, Rhizobium, and, Serratia,genera from the rhizosphere (Kuffner et al., 2008).

Induced systemic resistance:

Against particular stimuli, the physiological state of improved defensive ability of plants prompted and consequently, the plant's innate defenses are potentiated towards subsequent biotic challenges (Avis TJ et al.,2008). Biopriming plants along with some plant growths promoting rhizobacteria can also offer systemic resistance toward a broad spectrum of plant pathogens. Diseases of fungal, bacterial, and viral origin and in some instances even harm because of insects and nematodes can be decreased after the utility of plant growth-promoting rhizobacteria (Nazninet al., 2013). Likewise, triggered systemic resistance includes jasmonate and ethylene signaling within the plant and these hormones stimulate the host plant's protection responses against a kind of plant pathogens (Glick BR et al., 2012). Many individual bacterial precipitated systemic resistances together with lipopolysaccharides (LPS), flagella, siderophores, cyclic lipopeptides, 2, 4-diacetyl phloroglucinol, homoserine and, lactones, (Berendsen et al., 2012).

Commercialization of PGPR:

The commercialization and enhancement of plant growth-promoting rhizobacterial strains based on the linkages between industries, and scientific organization. the process of commercialization has gone through various stages likes as isolation of antagonist strains, screening, fermentation methods, mass production, viability, toxicology assay, industrial linkages, and field efficacy (Nandkumar et al., 2001). Furthermore, commercial achievement of PGPR strains is cost-effective and possible marketplace demand, protection and stability, extensive shelf life, low capital costs, and even availability of professional materials.Bioformulations are best defined as biologically energetic products comprising useful microbial strains in an easy-to-use and reasonable material. severalbioformulations are intended for field application, it is vital that appropriate carrier materials are used to keep cell viability beneath adverse environmental conditions. A specific quality formulation encouragesthe survival of bacteria maintaining the available population related to growth-promotingupshots on plants (Singh et al., 2014). Plant growth-promoting rhizobacterial bioformulation refers to arrangements of microorganisms that may be limited or completesubstitutes for chemical fertilization, and pesticides, supporting an environmentally sustainable practice to surge crop production (Arora et al., 2011).

Future Developmental Strategies for Sustainable Technology

An urgent need for hours to enhance the manufacturing process with high yield in addition to the fertility of soil to get in an eco-friendly manner in the world. Henceforth, the studies need to be emphasized with a better strategy of rhizome-engineeringmainly based on totally individual biomolecules, which creates a completely exclusiveplacement for the interaction among plants and microbes (Tewari S, Arora NK 2013). rhizosphere biology will govern the improvement of molecular and biotechnological approaches to increase our know-howin rhizosphere systems and extend an incorporated control of soil microbial populations. The replacement of multi-strain bacterial consortium over single inoculation may be considered an actual technique for reducing the deleterious impact of plant growth. The application of ice-nucleating plant growth-promoting rhizobacteria may be an operativeskill for strengthening plant growth at low temperatures(Nadeemet al.,2013). Further, research on nitrogen fixation and phosphate solubilization by plant growth-promoting rhizobacteria is in progress in the coming day, still,slight research and progress must be carried out on potassium solubilization which is the most important essential macronutrient for plant overall growth. Furthermore, advertising and marketing of bioinoculant products and the release of genetically modified crops into the eco-friendly environment might be alternative approaches for the registration of plant growth-promoting rhizobacterial mediators. Consequently, optimizing growth situations and increasing self-life toleratingunfavorable environmental circumstances, better yield, and cost-effectivenessof PGPR products are essential aspects of agriculturethat might be helpful for farmers(Basu et al., 2021).

Concluding remarks

PGPR, whichstimulates plant growth in rhizosphere soil isenormouslyuseful in incorporating various processes, like transforming, mobilizing, and solubilizing nutrients. These bacteria are the chief factors in the recycling of nutrients in the soil, resultantly, they are essential for soil fertility. They can be broadly used in agriculture to promote plant growth because they act as a source of plant nourishment and enrichment that would refill the nutrient cycle between the soil and plant roots. PGPR show detoxifying potential, and control phytopathogens, with a positive impact on crop production and ecosystem function. Extensive research and development might help in comprehending the microbial populations, and agroecosystemsthat may eventually lead to a sustainable agricultural system, in a better way to feed the ever-growing world population.

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Competing Interest:

The authors declare that they have no competing interests.

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