Available online at www.garmian.edu.krd

Passer Journal

Passer 6 (Issue 1) (2024) 124-129

http://passer.garmian.edu.krd/

Modifying Rhizobacteria for Improved Plant Growth and Soil Health in Sustainable Agriculture

Indrani Jadhav[1]*, Sudhir Singh[2], Apurva Kumar R Joshi[3]

[1]**School of Life and Basic Sciences, Jaipur National University, Jaipur, India,*

[2]*Department of Microbiology, TeerthankerMahaveer University, Moradabad, Uttar Pradesh, India,*

[3]*Department of Biochemistry, School of Sciences, JAIN,Bangalore, India,*

Received 29 May 2023; revised 27 November 2023;
accepted 31 January 2024; available online 13 February 2024

DOI: 10.24271/PSR.2023.399649.1334

ABSTRACT

Soil health is the soil quality that promotes and sustains plant development, increasing efficiency while preserving long-term ecological quality. A significant population of creatures that encourage plant growth, like the Plant Growth Promoting Rhizobacteria (PGPR), are the essential elements of healthy soil. In the rhizosphere soil, PGPR has various categories of ecologically advantageous functions. The ability of PGPR to clean up the environment is one of their other crucial functions. In this article, we examine the current study on the many processes of PGPR in sustaining healthy agricultural soil conditions, hence lowering (or eliminating) the dependency on harmful agrochemicals. This review thoroughly explains the present PGPR core processes to have more agroecological practices for sustainable agriculture. It is used as a soil rhizoremediator, biocontrol agent, and plant growth booster. Utilizing PGPR, which has the potential to function as an effective bioprotectant, is the only natural option to preserve soil health. The findings illustrate the extent of phosphate solubilization across different time intervals and in the presence of various phytopathogens. In the final Analysis, Sustainable agriculture stands to benefit greatly from research into manipulating rhizobacteria for enhanced plant development and soil health.

Keywords: Rhizomemediators, Soil Health, PGPR, Growth Stimulator. Rhizobacteria.

1. Introduction

The importance of sustainable agriculture in addressing global food security and environmental problems is growing. The need for food increases along with the global population, increasing pressure on agricultural systems to produce more while minimizing negative environmental effects[1]. The significance of healthy soil and encouraging plant development in this environment cannot be emphasized[2]. Using advantageous plant-microbe interactions, like those involving rhizobacteria, has become a possible tactic for increasing agricultural output and sustainability. Using rhizobacteria is an easy way to improve soil health and plant growth[3]. Rhizobacteria are minuscule organisms that live in the rhizosphere, the region around a plant's roots, where they engage in complex interactions that may affect the health and productivity of the plant. Researchers seek to genetically edit these Rhizobacteria to create bio-fertilizers and bio-stimulants as alternatives to current chemical pesticides and fertilizers[4]. Plants and rhizobacteria interact in a way that is advantageous to both.

Rhizobacteria may aid in the development of plants by producing hormones, preventing illnesses, and cycling nutrients[5]. For instance, some Rhizobacteria strains can convert atmospheric nitrogen into a form that plants can utilize, decreasing the need for manufactured nitrogen fertilizers and lowering environmental pollution. These microorganisms may also create enzymes that help plants acquire nutrients by dissolving complicated organic materials. Modified Rhizobacteria improve soil fertility and sustainability by reducing nutrient loss and increasing availability[6]. Additionally, certain Rhizobacteria can defend plants from dangerous diseases. Acting as natural bio-pesticides, they may boost the plant's immune system and completely eradicate disease-causing microbes[7]. This encourages a healthy agricultural ecology and lessens dependency on chemical pesticides. Auxins and cytokinins, two growth-promoting compounds that affect plant development and stress tolerance, may also be produced by transgenic Rhizobacteria[8].

We used root colonizing bacteria (PGPR) in this work because they could enhance plant growth and development either directly or indirectly. The industry of sustainable agriculture benefits from PGPR. This study thoroughly explains the moment PGPR core systems and programs such as soil rhizoremediators, biocontrol agents, and plant growth stimulators. This study

* Corresponding author
E-mail address: indranijadhav@jnujaipur.ac.in (Instructor).
Peer-reviewed under the responsibility of the University of Garmian.

highlights the role of PGPR systems, focusing on their functionality in improving soil health and their substantial contribution to sustainable agricultural productivity.

2. Literature review

The study[9] determined that plants experience various biotic and abiotic challenges and developed many direct and indirect ways to deal with these pressures. Diverse microbial communities with different functional niches may be found in soil. Crops are associated with multiple helpful microorganisms, including bacteria and fungi, for optimum development and protection advantages. These bacteria have various hosts and may survive within and outside plant tissue. The article[10] discussed the development of the crop-microbe-soil complex and the biochemical pathways under the influence of agriculture that are accountable for soil health, as well as recent changes to the idea of soil quality and health in agriculture-systems, as well as the main indicators now used to measure soil health.

Additionally, it addressed agroecosystem problems that primarily impact soil health, particularly soil nutrient deficiencies. The study[11] discussed the selection and formulation of effective N-fixing bacteria as biofertilizers, as well as a thorough understanding of the variety of nitrogen-fixing microorganisms and the processes of fixation, which are all necessary for that optimization. If the BNF mechanism is well understood, it may be possible to transfer that ability to non-leguminous plants or similar non-fixing bacteria. The minireview provides a quick overview of the BNF, the nitrogen fixation cycle and processes, the market worth of biofertilizers, and their usage in agriculture.

The purpose of the article[12] was to provide suggestions on methods to enhance the process of encouraging plant development. There is a separate group of microorganisms known as plant growth-promoting Rhizobacteria that, in one way or another, mitigate the effects of both biotic and biotic stressors. The ecology of plants is particularly vulnerable to negative influences from the environment. Numerous biotic and abiotic variables encountered daily function as direct or indirect causes for the underdevelopment of plants that eventually result in disease. Numerous indigenous microbial flora are found in aquatic and soil systems used for agriculture. The study[13] determined whether MPs pose a new risk to the health of plant-soil relationships in agroecosystems. Evaluate the ecological dangers MPs provide to the interactions between plants, microbes, and soil and discuss how MPs affect soil carbon, nutrient cycling, and greenhouse gas emissions in agroecosystems.

Additionally, the breakdown of compostable MPs produces more accessible C that boosts microbial and enzymatic activity, perhaps speeds up SOM mineralization, and heightens plants and microbiological competitiveness for nutrients. In the review[14], they spoke regarding the way soil microbial populations and plant-microbe interactions are affected by climate change. Maintaining healthy soil is essential for agricultural sustainability and significantly impacts agroecosystems' productivity. In contrast, several human processes, such as climate change, pose serious challenges to soil resources. Agriculture and ecosystems are more unpredictable and complicated by climate change, threatening sustainability. Relationships between plants and microbes improve plant growth and resilience to biotic and biotic stresses. Understanding how ecosystems respond to changing environmental conditions requires tying the distribution of microbial diversity and ecological functioning together.

The goal of the research[15] was to isolate, identify, and characterize bacterial entophytes from two native medicinal plants that grow in the arid South Sinai region. It also indicates these endophytes' characteristics that promote plant development. These bacteria were examined for their capacity to support plant growth using morphological and biochemical approaches, greenhouse testing, and the isolation of 13 probable bacterial entophytes from both plant species' leaves. They were applied to maize plants to assess further the PGPR capabilities of selected endophytic bacterial strains in greenhouse settings. The activity of isolated bacterial strains that promote plant development may vary. Due to their relationship with bacterial endophytes, desert plants can withstand the severe environmental challenges typical of arid and semiarid locations.

2.1 The rhizosphere as an Ecosystem

The rhizosphere is a term used to describe the area around the roots immediately impacted by plant root secretions. Due to their role in nutrient intake and defense against pathogen attack, microbial activity in this zone is crucial for the health of plants. The interaction between the plant, the soil, and the microorganisms results in several procedures that affect the health and production of the plant. It is widely known that rhizobacteria connection and interaction with the roots of a plant inside the rhizosphere are responsible for the effective encouragement of plant development. The visibility of nutrients in the rhizosphere is enhanced, while PGPR is employed throughout root settlement, encouraging plant expansion and growth. Crops generate a range of compounds in the manner of discharges from the roots, known as the rhizosphere. Carbohydrates, organic acids, proteins, flavonoids, amino acids, and fatty acids are all examples of such molecules. The root exudates in rhizospheric soil operate as communication molecules among seeds and various rhizobacteria species. Rhizodeposition, lysates, mucilage, mucigel, root exudates, and root debris are the key sources of organic matter in the soil — the primary sources of organic matter. Rhizospheric is a highly territorial micro-ecosystem where all inhabitants compete with one another to settle down the greatest root sections and occupy ecological gaps for survival since all nutrients are readily available. Rhizobacteria comprise a variety of biological mechanisms that have developed and evolved to survive in these challenging settings.

2.2 Rhizobacteria's role in promoting plant development and soil health

The establishment of plant growth Rhizobacteria is a general term specifically used to characterize different types of bacteria which engage in a range of processes, providing a substantial impact on plant growth, productivity, and disease resistance. They establish a beneficial and competitive link with plant root systems. Plant growth rhizobacteria is a general word that particularly relates to bacterial species that significantly influence yield, plant development, and disease resistance through various mechanisms through the creation of beneficial and competitive relationships to plant root structures. Increased antioxidant activity, phenolic content, and photosynthetic pigments are ways that PGPR might boost the nutritional value of commercially significant plants. Some of the most important vegetables and plants, along with soybeans and lettuce, have reported enhanced nutrient concentration for healthy effects after the vaccination of PGPR, species of Azotobacter, Pseudomonas, and Bacillus. In addition to their metabolic adaptability to digest categories of xenobiotic and natural chemicals, the flexibility of PGPR is excellent in various soil conditions. It is not at all unexpected that the combined implementation of PGPR therapies has been exhibited to be more effective than only one therapy alone in contained pathogens, considering their advantageous effects and mode of operation. Various PGPR processes and forms are extensively used to produce agricultural characteristics. The many PGPR types that have favorable methods and are essential bioremediations, biostimulants, and crop protectors are listed in Table 1.

Table 1: The function of rhizosphere and bulk bacteria in plant biofertilization.

Role	Bacterial species	Beneficiated plant	Exerted mechanisms
Biofertilization	*Acetobacterdiazotrophicus*	-	Nitrogen fixation
Biofertilization	*Bacillus filamentosus*	Alfalfa	Zinc solubilization
Biofertilization	*Bacillus mojavensis*	Maize	Potassium solubilization
Biofertilization	*Bacillus tequilensis*	-	Ammonia production
Biofertilization	*Enterobacter oryzae*	Mangart and Jam	Nitrogen fixation
Biofertilization	*Lysinibacillussphaericus*	Rice	Nitrogen fixation
Biofertilization Bioprotection	*Pseudomonas fulva*	Wheat, Scots pine	Phosphate solubilization Siderophore production
Biofertilization	*Pseudomonas orientalis*	Rice	Potassium solubilization
Biofertilization	*Sphingomonas true peril*	Acacia acuminate	Nitrogen fixation
Bioprotection	*Bacillus pantothenic's*	Maize	Protease production
Bioprotection	*Bacillus velezensis*	Tomato	Bioprotection
Biostimulation	*Advenellakashmirensis*	-	Cytokinin production
Biostimulation	*Kocuriae rythromyxa*	Peanut	IAA production
Biostimulation	*Pseudomonas plecoglossicida*	Pearl millet	IAA production

2.3 Direct and indirect plant benefits from PGPR

Direct and indirect effects of PGPR on plant growth include the production of stimulants, the improvement of soil nutrient absorption, and the protection of plants against pathogen infection. Hence, PGPR cares for soil and plant health by creating a variety of chemicals that promote crop development and act as antimicrobials, some of which may be eliminated or spread in solid intermediate and some of which can be volatile. The positive function of PGPR, with a considerable effect on agricultural sustainability, depends upon identifying such processes or employing indirect methods for boosting plant development.

2.4 Plants benefit directly and indirectly from PGPR.

Directly and indirectly, PGPR fosters plant growth by producing stimulants, improving soil nutrient absorption, and protecting plants from pathogen infection. Hence, PGPR cares for soil and plant health by creating a variety of chemicals that promote crop development and act as antimicrobials, some of which may be eliminated or spread in solid intermediate and some of which can be volatile[15]. The positive function of PGPR, with a considerable effect on agricultural sustainability, depends upon identifying such processes or employing indirect methods for boosting plant development.

2.4.1. Biological nitrogen fixation

The method recognized as "Biological Nitrogen Fixation (BNF)" involves nitrogen-fixing bacteria that use a complicated enzyme operation known as nitrogenize to transform atmospheric elemental nitrogen into forms that plants can utilize. A significant amount of the basic nitrogen that goes into the soil naturally is fixed through PGPR and other helpful soil microbes. Therefore, creating organic fertilizers considerably benefits from interactions between plant microbes via biological nitrogen fixation. The production cost may decrease by using nitrogen-fixing bacteria instead of artificial fertilizers. Less chemical N fertilizer usage and more nutrient availability occur from PGPRs with nitrogen-fixing capabilities as they may offer higher organic nitrogen and additional crucial nutrients in the soil. Moreover, when rhizobacteria species are combined, the soil's health is improved, and sustainable agriculture is ensured, as opposed to when a single species is applied. The significance of the intricate connections among conventional nitrogen fixes, including rhizobia groups, along with other saprophytic bacteria frequently considered species that support plant development, is highlighted by the current studies[16].

2.4.2. Solubilization of phosphate

Phosphorus stands out as the pivotal nutrient for the growth and development of plants. Its involvement extends across virtually all primary metabolic processes in crops, encompassing crucial functions such as photosynthesis, respiration, the electron transfer chain, the synthesis of significant molecules, and the transmission of signals. Due to phosphate fertilizers' fixation in the soil as insoluble structures, plants may absorb small quantities of each other. In addition to being expensive, frequent use of phosphatic fertilizers is not a sustainable practice. For increasing crop production in low P soils under this circumstance, it is necessary to look for an ecologically sound and environmentally benign technique. The transformation of insoluble phosphate complexes by several PGPRs has been reported to occur via several processes. According to reports, PGPR makes phosphorus accessible to plants by solubilizing and mineralizing complicated P components. Bacterial synthesis of organic acids, whether in a laboratory setting or outdoors, chelates mineral ions and lowers the pH of the medium, allowing P to enter the soil solution. Phosphatizes are enzymes that are expelled from the cell and convert organic forms of phosphorus into inorganic forms. When P is converted into simpler forms, both its organic and inorganic forms may be readily absorbed by plants. Creating bacterial inoculants that can generate these enzymes is desirable due to their vital role in phosphate solubilization since they may be of significant practical benefit in sustainable agriculture[17]. Figure 1 shows the highest level of phosphate solubilization at different time durations.

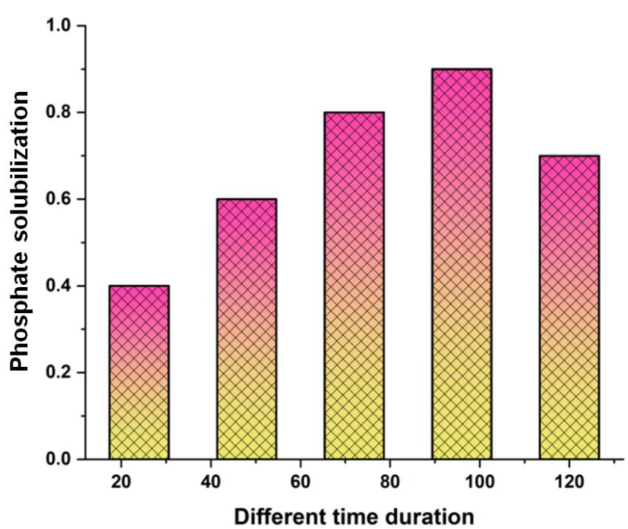

Figure 1: The maximal solubilization of phosphate during various periods.

2.4.3. Potassium solubilization

The application of potassium-solubilizing PGPR has elevated soil levels of potassium, enhanced plant potassium uptake, and boosted the development of commercially significant crops involving rape, cotton, cucumber, pepper, grain, and peanut. Potassium availability is the most prevalent crucial component in controlling cell development. They apply to many processes in crops, including the growth of hair roots, the increase in pollen tubes, the control of the water pressure inside plant cells, and the flow of many different substances. The considerable drop of mica, feldspar, and clay silicates from calcite, sandstones, granite, and dolomite of limestone produces citrate, oxalate, acetate, and other organic acids. Crops may obtain more nutrients with chemical acids by converting insoluble potassium into soluble potassium[18]. Well-known “Bacillus species produce carboxylic acids that solubilize potassium complexes in soil” and increase soil fertility and agricultural efficiency as shown in Figure 2.

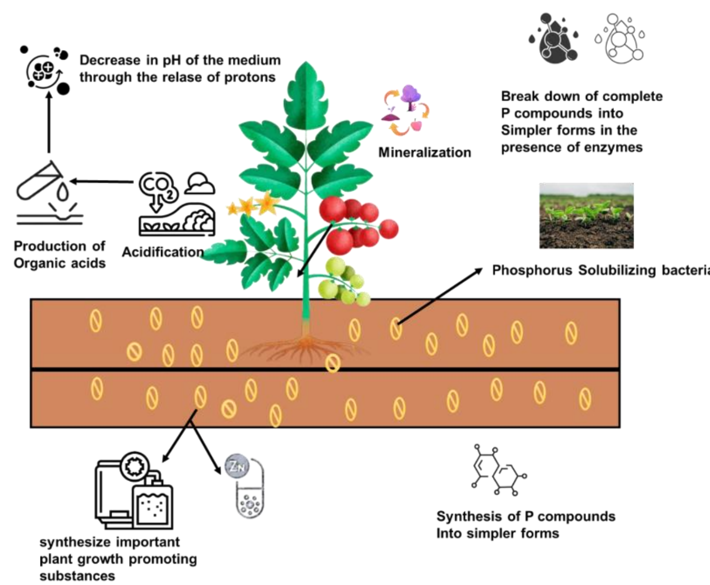

Figure 2: Potential pathways for phosphate-solubilizing rhizobacteria's encouragement of plant development are shown schematically.

2.4.4. Zinc solubilization

In plant life, zinc primarily contributes to the production of cytochrome, the metabolism of carbohydrates. Zinc is a coenzyme for selecting reactions of enzymes, ensuring the stability of ribosomal division, and the ejection of hormonal substances that support progress, the integrity of membranes within cells, the development of floral tissue, and the growth of pollen pipes. A small quantity of zinc is obtainable in the soil in solution. Still, the bulk of the metal is shown as insoluble mixes and minerals because plants may utilize zinc as a divalent particle. There are several ways to solubilize zinc, such as proton extrusion, the release of various compounds, or the creation of chelating substances that damage zinc complexes. Zinc is also made more soluble through ZSR because it produces both organic and inorganic substances acids, including chemical acids such as sulphuric, carbonic, and nitric. In light of this, the Injection of plants with ZSR may be useful not just in addressing the concerns through enhancing nutritional practices and malnutrition regarding the material but also in offering the finest alternatives for applying zinc fertilizer to soils with accessible zinc sources as shown in Figure 3.

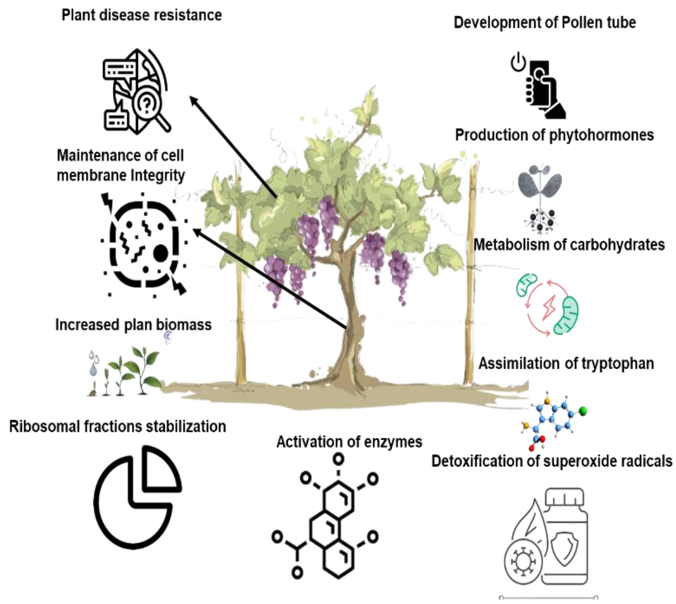

Figure 3: Potential candidates for improving plant health include Rhizobacteria that solubilize zinc.

2.4.5. 1-aminocyclopropane-1-carboxylate (ACC) deaminase

The inoculation of bacteria producing 1-aminocyclopropane-1-carboxylate deaminase (ACCD) is a powerful biological method to control the development and endurance of the challenge crop by lowering ethylene production. The evolution and expansion of plants are encouraged by the gaseous crop hormone ethylene. Except for when the fruit is growing and ripening, nearly every higher plant parts and tissues manufacture it at lower levels. If rhizobacteria that make ACCD are present, the ACC that plant roots create in rhizospheric soil is broken down, and after that, ACC secretion from the seeds is encouraged, which results in a drop in ACC contents in both the roots and the leaves. It has also been proposed that PGPR with ACCD activity, such as that seen in Pseudomonas sp. strain UW4, cooperates with other bacterial defenses against salt stress, such as trehalose production. Numerous species, especially nitrogen-fixing rhizobia, have been shown to contain trehalose, which acts as an osmoprotectant against a range of stresses, including salt and dehydration[19]. Thus, ACC deaminase would take on new roles in connection with other beneficial PGPR activities.

2.4.6. Siderophores

Siderophores are tiny molecules produced by bacteria, fungi, and other microbes to aid in iron absorption from their surroundings. Iron is an important nutrient for many species because it is necessary for several biological activities, including DNA synthesis, respiration, and metabolism.

The only way to preserve the health of the soil naturally is by using PGPR, which may act as a powerful bioprotectant. The synthesis of iron-chelating substances, also known as siderophores, was one of the first methods to be documented for inhibiting phytopathogen. Rhizobacteria that produce siderophores may be used as biocontrol substances since iron-chelating chemicals have been shown to have antifungal effects by depriving plant infections of this important component.

2.4.7 Volatile organic compounds (VOCs)

PGPR interacts with plants or additional rhizosphere microbes to create VOCs with various operations and functions. There is a ton of data to support the idea that VOCs have two direct and indirect impacts on processes that promote plant development, meaning that rhizosphere VOCs may directly or indirectly stimulate crop growth by limiting the proliferation of possible phytopathogen. Pathogens are negatively affected by the volatile hydrogen cyanide by blocking the electron transport pathway, which results in cell death; it is crucial for preventing infections. In light of the indirect boost in phosphate accessibility in the rhizosphere caused by volatile organic molecules, nearby plants gain.

2.4.8. Manufacturing of hydrolytic enzymes

Chitinases, pectinases, catalases, cellulases, and proteases are among the hydrolytic enzymes that PGPR makes and excretes. It has been shown that this enzyme's defense-related actions are effective against multiple phytopathogens. In the fungal cell wall, chitin plays a significant structural role. Chitin breakdown occurs as a consequence of Rhizobacteria that support plant development attacking the cell walls of fungi. By doing so, chitinolytic bacteria prevent the growth of fungi that cause diseases, such as the more than 200 plant species-infecting Botrytis cinerea phytopathogen that causes gray mold. It is generally known that cellulose-producing bacteria may operate as a barrier to the spread of fungi. Figure 4 demonstrates the effectiveness of various PGPRs as opposed to a variety of phytopathogens.

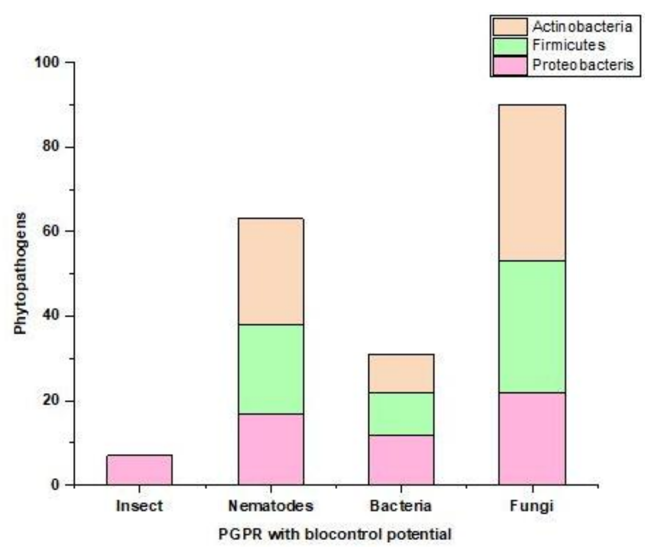

Figure 4: Biocontrol effectiveness for various PGPR against diverse phytopathogens.

3. PGPR's Environmental Clean-Up

The term "bioremediation" is used to describe the practice of cleaning polluted environments using biological substances and methods. An alternative to conventional techniques for removing contaminated soil with metals is bioremediation.The innate capacity of metal-resistant plant growth-promoting rhizobacteria in metal-polluted soils to ameliorate soil characteristics is greater than in typical agricultural operations.While most metals are considered hazardous, there is a lot of variation in their degrees of toxicity[20]. The metals cadmium and lead eliminate the organism by attaching to breathing enzymes and damaging the soil organisms oxidatively by producing reactive oxygen forms.

Conclusion

It is crucial to uncover the probable mechanisms of PGPR action and its advantageous effects on crops to promote plant development and output. With the world's population expected to reach 10 billion by 2050 and peak between 2070 and 2080, this measure was essential to meet the never-ending need for food. In conclusion, manipulating rhizobacteria for improved plant growth and soil health presents a transformative opportunity in sustainable agriculture. In this work to secure food security for an expanding world population while reducing farming's negative environmental effects, sustainable agriculture is becoming more and more crucial. To boost crop yields, use fewer chemicals, and benefit ecosystem health, for agriculture to be sustainable, greater plant growth and healthy soil are important. The development of an environment favorable for plant growth and a sustainable ecological balance is encompassed by soil health, and it is of utmost significance in contemporary agricultural operations. PGPR is essential for enhancing farming systems and is a key element contributing to soil health. Along with nutrient cycling, phytopathogen suppression, immunological priming in plants, and direct promotion of plant growth via hormone and metabolite synthesis, PGPR in the rhizosphere performs various ecologically useful tasks. Future research might focus on adapting PGPR strains for individual crops, enhancing their nutrient-fixing ability to satisfy specific soil and plant needs.

Conflict of interests

None

References

1. Rasheed, M.S., 2023. Solubility of Iron (Fe II) in the Long Term Vegetable Growing in Calcareous Soils. Passer Journal of Basic and Applied Sciences, 5(1), pp.103-109.
2. Dogara, A.M., Hamad, S.W., Halliru, B.S., Wada, N. and Dalorima, T., 2022. Influences of different concentrations of herbicides on the growth and yield of maize as well as their effects on the associated weeds in North-Western Nigeria. Passer Journal of Basic and Applied Sciences, 4(1), pp.31-36.
3. Khurshed, D.N. and Jumaa, M.E., 2022. Medicinal plant feeding impact with different levels on meat quality in Hubbard broiler chicken. Passer Journal of Basic and Applied Sciences, 5(1), pp.13-16.
4. Omer, S.A., Faraj, I.M. and Faraj, N.M., 2023. Invitro Inhibitory Effect of Some Plants Aquatic Extracts on Conidial Growth of the Phytopathogenic Fungus (Fusarium oxysporium). Passer Journal of Basic and Applied Sciences, 5(2), pp.342-347.
5. Mohammed, M.S. and Towfiq, S., 2022. MULTI-ENVIRONMENT TEST FOR STABILITY AND ADAPTABILITY USING LINE X TESTER CROSSING DESIGN IN MAIZE. Passer Journal of Basic and Applied Sciences, 4(2), pp.197-204.
6. Salih, K.J., 2022. Purification of cytosolic ribosome in Arabidopsis thaliana using different proteases. Passer Journal of Basic and Applied Sciences, 4(1), pp.78-85.s
7. Qader, M.Q. and Shekha, Y.A., 2023. Potential of Fungal-Microalgal species in the Environmental Biotechnology. Passer Journal of Basic and Applied Sciences, 5(1), pp.52-58.
8. Najmuldeen, H.H.R. and Razaq, C.H., 2023. Evaluation the Impact of Chlorination on the Development of Chlorine and Antibiotic-Resistant Bacterial Isolates in Public Swimming Pools. Passer Journal of Basic and Applied Sciences, 5(1), pp.110-120.
9. Ahmad, I. and Zaib, S., 2020. Mighty microbes: Plant growth promoting microbes in soil health and sustainable agriculture. Soil Health, pp.243-264.
10. Yang, T., Siddique, K.H. and Liu, K., 2020. Cropping systems in agriculture and their impact on soil health-A review. Global Ecology and Conservation, 23, p.e01118.
11. Soumare, A., Diedhiou, A.G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S. and Kouisni, L., 2020. Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. Plants, 9(8), p.1011.
12. Rai, P.K., Singh, M., Anand, K., Saurabh, S., Kaur, T., Kour, D., Yadav, A.N. and Kumar, M., 2020. Role and potential applications of plant growth-promoting rhizobacteria for sustainable agriculture. In New and future developments in microbial biotechnology and bioengineering (pp. 49-60). Elsevier.
13. Zhou, J., Wen, Y., Marshall, M.R., Zhao, J., Gui, H., Yang, Y., Zeng, Z., Jones, D.L. and Zang, H., 2021. Microplastics as an emerging threat to plant and soil health in agroecosystems. Science of the Total Environment, 787, p.147444.
14. Dubey, A., Malla, M.A., Khan, F., Chowdhary, K., Yadav, S., Kumar, A., Sharma, S., Khare, P.K. and Khan, M.L., 2019. Soil microbiome: a key player for soil health conservation under changing climate. Biodiversity and Conservation, 28, pp.2405-2429.
15. ALKahtani, M.D., Fouda, A., Attia, K.A., Al-Otaibi, F., Eid, A.M., Ewais, E.E.D., Hijri, M., St-Arnaud, M., Hassan, S.E.D., Khan, N. and Hafez, Y.M., 2020. Isolation and characterization of plant growth promoting endophytic bacteria from desert plants and their application as bioinoculants for sustainable agriculture. Agronomy, 10(9), p.1325.
16. Khatoon, Z., Huang, S., Rafique, M., Fakhar, A., Kamran, M.A. and Santoyo, G., 2020. Unlocking the potential of plant growth-promoting rhizobacteria on soil health and the sustainability of agricultural systems. Journal of Environmental Management, 273, p.111118.
17. Bellenger, J.P., Darnajoux, R., Zhang, X. and Kraepiel, A.M.L., 2020. Biological nitrogen fixation by alternative nitrogenases in terrestrial ecosystems: a review. Biogeochemistry, 149, pp.53-73.
18. Prabhu, N., Borkar, S. and Garg, S., 2019. Phosphate solubilization by microorganisms: overview, mechanisms, applications, and advances. Advances in biological science research, pp.161-176.
19. Liu, C.H., Siew, W., Hung, Y.T., Jiang, Y.T. and Huang, C.H., 2021. 1-Aminocyclopropane-1-carboxylate (ACC) deaminase gene in Pseudomonas azotoformans is associated with ameliorating tomato salinity stress. Journal of Agricultural and Food Chemistry, 69(3), pp.913-921.
20. Katiyar, P., Pandey, N. and Sahu, K.K., 2020. Biological approaches of fluoride remediation: potential for environmental clean-up. Environmental Science and Pollution Research, 27, pp.13044-13055.