ROLE AND IMPORTANCE OF PLANT GROWTH PROMOTING RHIZOBACTERIA IN MODREN DAY AGRICULTURE BY IMPROVING SOIL RIZOSPHERE: A REVIEW

Abstract

The expanding human population necessitates more food production, but this must be done in the face of worsening climate change and a limiting supply of farmland. Today's challenge is to increase agricultural production demand while lowering the use of synthetic chemical fertilisers and pesticides. Growing need for agricultural production while reducing the usage of synthetic chemical fertilisers and pesticides has become a major problem in recent years. Plant growth-promoting rhizobacteria (PGPR) plays a vital part in the agriculture industry's sustainability. PGPR is an ecologically friendly method of improving agricultural yields by stimulating plant development via a direct or indirect process. PGPR regulates hormonal and nutritional balance, induces resistance against plant diseases, and solubilizes nutrients for easier absorption by plants, among other things. Furthermore, PGPR exhibits both synergistic and antagonistic interactions with microorganisms in the rhizosphere and in bulk soil, which improves plant growth rate indirectly. PGPR regularly establish mutualistic interactions with host plants related to nutrient absorption (N fixation, P and K solubilization, and siderophore production), enhanced stress resistance (abiotic and biotic), and regulation of plant development and physiology through signal compound production, including phytohormones and specific inter-organism signal compounds, could be used as a more sustainable agricultural approach. Root exudates, which are released into the rhizosphere by host plants as a reduced carbon supply for phytomicrobiome members, also aid in providing a stable environment for microbe development. Given the benefits of PGPR in terms of biofertilization, biocontrol, and bioremediation, all of which have a favourable impact on crop yield and ecosystem functioning, its use in agriculture should be encouraged. With the advancement of technology in the establishment of effective research and development, PGPR utilisation will undoubtedly become a reality and will be helpful in critical processes that assure the stability and productivity of agro-ecosystems, bringing us to a perfect agricultural system.

Keywords: PGPR, Soil Improvement, Siderophores, HCN, rhizomicrobiome, Nanoencapsulation.

Introduction

Microbes actively involved in crop production are generally termed plant growth-promoting bacteria (PGPB), whereas the bacteria isolated from the root zone are termed PGPR. Kloepper and Schroth (1978) coined the term Plant Growth Promoting Rhizobacteria (PGPR) "the soil bacteria that colonize the roots of plants by following inoculation onto seed and that enhance plant growth". “Plant growth-promoting rhizobacteria (PGPR) are bacteria that invade plant roots and stimulate plant development. The rhizosphere is the limited zone of soil impacted primarily by the root system" (Dobbelaere et al., 2003). "Because of the accumulation of a variety of plant exudates, such as amino acids and sugars, this zone is rich in nutrients as compared to the bulk soil, offering a rich supply of energy and nutrition for bacteria" (Gray and Smith, 2005). Plant growth-promoting rhizobacteria (PGPR) encourage the growth of their host plant and increase the rhizospheric bacterial population resulting noticeable influence on plant growth and yield. Plant growth-promoting rhizobacteria (PGPR) play a significant part in the sector of sustainable agriculture. Food production must be quadrupled by 2050 to fulfil global food demand; overexploitation of fertile areas employing unsustainable ways may alleviate food demand difficulties but also has significant environmental consequences. Increasing agricultural output demand while reducing the usage of synthetic chemical fertilisers and pesticides is a major problem today. Fertilizer and pesticide overuse contribute to climate change through greenhouse gas emissions (GHG) and hazardous soil deposition. At this critical juncture, there is an urgent need to transition to more sustainable crop production practises, ones that focus on promoting sustainable mechanisms that allow crops to grow well in resource-limited and environmentally challenging conditions, as well as developing crops with greater resource use efficiency that have optimum sustainable yields across a broader range of environmental conditions. The usage of PGPR is an ecologically friendly method of enhancing agricultural yields by encouraging plant development via a direct or indirect process. PGPR regulates hormonal and nutritional balance, induces resistance against plant diseases, and solubilizes nutrients for easy absorption by plants. The use of the PGPR is becoming more common in the agriculture business due to its sustainable and ecologically favourable plant growth promotion mechanisms. As a result, in this chapter, we stress the role of beneficial plant growth-promoting rhizobacteria (PGPR), in long-term plant growth and production enhancement in the face of climate change. Furthermore, the functions of soil-dwelling microorganisms in stress reduction, nutrient delivery (nitrogen fixation, phosphorus solubilization), and PGPR synthesis, as well as the variables that may alter their effectiveness, have been widely addressed. PGPR exhibits both synergistic and antagonistic interactions with microorganisms in the rhizosphere and bulk soil, which indirectly increases plant growth rate.

Table 1. Diversity/ Types of PGPR

extracellular-plant growth promoting rhizobacteria (e-PGPRs)	**intracellular-plant growth promoting rhizobacteria (i-PGPRs)**
extracellular-plant growth promoting rhizobacteria (e-PGPRs): represents the microbial species that inhabit the rhizosphere over the rhizoplane or Bacteria living outside plant cells and not producing nodules, but enhancing plant growth. Bacteria that live outside of plant cells do not produce nodules but promote plant development. Enhance plant disease resistance.	intracellular-plant growth-promoting rhizobacteria (i-PGPRs): represents the bacteria present in the intermediate spaces of the root cell cortex or within specialised structures called nodules.
Azospirillum, Azotobacter, Agrobacterium, A	Endophytic bacteria that represent the iPGPR

enterobacter, *Serratia*, *Bacillus*, *Caulobacter*, *Chromobacterium*, *Erwinia*, *Flavobacterium*, *Micrococcus*, *Pseudomonas*, and *Burkholderia* are the bacterial genera covered in GPR.	include *Rhizobium*, *Bradyrhizobium*, *Allorhizobium*, *Mesorhizobium*, and *Frankia* species.

(Gray and Smith 2005).

PGPR stimulates plant development through two major pathways known as (I) direct and (II) indirect.

How PGPR facilitate plant growth?

Direct

- ➢ Biological nitrogen fixation
- ➢ Phosphate solubilization
- ➢ Phytohormone production
    - IAA
    - Cytokinins
    - Gibberellins

Indirect

- ➢ Biocontrol agents
- ➢ Antibiotic production
- ➢ Siderophore production
- ➢ HCN production
- ➢ Production of lytic enzymes
- ➢ Cometition and displacement of pathogens
- ➢ Modification of plant metabolism
- • Stimulation of plant defense pathways
- • Modification of plant ethylene levels

Production of phytohormones

At extremely low concentrations, phytohormones are naturally occurring organic chemicals that regulate numerous physiological or morphological processes in plants, such as cell elongation and cell division. These phytohormones have a noticeable effect on plant metabolic activity and have also indirectly contributed to the stimulation of defence as well as abiotic stress management. Drought, salinity, heat, cold, flooding, and ultraviolet radiation are severe problems that result in massive crop losses worldwide. PGPR secretes a variety of phytohormones, including auxin, cytokinin, ethylene, gibberellins (GA), and abscisic acid (ABA).

“**Indole acetic acid** is the most important hormone and physiologically active hormone generated by 80 percent of PGPR and promotes various growth and developmental processes such as cell division, elongation, and differentiation. The most prevalent bacterial taxa involved in the manufacture of IAA in the rhizosphere of various crops include *Acinetobacter*, *Pseudomonas*, *Rhizobium*, *Azospirillum*, *Bacillus*, and *Klebsiella*. *Pseudomonas* spp. are the most potent producers of IAA among these bacterial taxa, with *Pseudomonas putida* producing more IAA than *Pseudomonas fluorescens”* (Singh et al.,2019).

“**Gibberellin** is essential for seed germination and emergence, floral induction, flower and fruit development, and steam and leaf growth; whereas GA's most prominent physiological action is shoot elongation” (Egamberdieva et al., 2017). “Gibberellin is generated naturally by higher plants, fungi, and bacteria” (Patel and Minocheherhomji, 2018). *Acetobacter diazotrophicus, Azospirillum lipoferum, Bacillus pumilus, Bacillus cereus, Bacillus macrolides, Herbaspirillum seropedicae,* and *Acinetobacter calcoaceticus* are among the PGPR that produce GA.

“**Ethylene** is a vital phytohormone with several biological roles, including plant growth and development. It encourages root initiation, limits root elongation, lowers wilting, improves fruit ripening, increases seed germination, and stimulates the synthesis of other plant hormones”(Ahmed et al.,2017). “The presence of 1-aminocyclopropane-1-carboxylate (ACC) deaminase-generating PGPR plays an active role in ethylene level adjustment in plants” (Singh et al., 2019). “Bacterial ACC deaminase synthesis *Pseudomonas, Bacillus, Acinetobacter, Azospirillum, Achromobacter, Enterobacter, Burkholderia, Agrobacterium, Alcaligenes, Rhizobium, and Serratia* are among the genera” (Ahmed et al.,2017).

“**Cytokinins** are a kind of phytohormone that promotes cell division, cell enlargement, and tissue growth in particular plant tissues. Plant responses to exogenous cytokinins promote seed germination, bud release from apical dominance, stimulation of leaf expansion and reproductive development, senescence retardation, enhanced cell division, enhanced root development, inhibition of root elongation, shoot initiation, and certain other physiological responses. Plant growth control is influenced by cytokinin-producing bacterial species such as *Pseudomonas, Klebsiella, Enterobacter, Achromobacter, Bacillus, Paenibacillus, Azotobacter, Agrobacterium, Azospirillum, Flavobacterium,* and *Arthrobacter”* (Patel and Minocheherhomji, 2018). The production provides PGPR with competitive benefits that may colonise roots and drive other microbes out of this ecological niche in highly competitive environmental circumstances, the capacity to get iron through siderophores may influence the outcome of several competitions Carbon sources made available by root exudation as well as rhizodeposition.

Production of Siderophores

“Plants and other photosynthetic organisms require iron because it functions as an enzyme cofactor in a variety of metabolic activities including photosynthesis, amino acid synthesis, respiration, nitrogen fixation, and oxygen transport. Iron is one of the most prevalent elements in the earth's crust; it occurs in two oxidation states: Fe2+ and Fe3+, with the latter being significantly less accessible to plants due to the development of insoluble iron oxides/hydroxides” (Zuo and Zhang, 2011). “Plant growth-promoting bacteria (PGPB) have been shown to sequester iron from the soil by producing low molecular weight compounds (400–1,500 Da), according to research. Siderophores are iron-chelating chemicals that can bind ferric ions and make iron easily accessible for absorption by plant ++cells” (Goswami et al.,2016). “Furthermore, PGPB siderophores have a far greater affinity for iron sequestration than those generated by fungi or the plant itself” (Saha et al., 2016). “Many microorganisms from both marine and terrestrial habitats have been isolated and tested for their potential to create siderophores” (Sandy and Butler, 2009; Rezanka et al., 2018). “So far, about 500 terrestrial and marine siderophores with various chemical architectures have been discovered” (Chu et al., 2010; Hider and Kong, 2010). “Phenolates, hydroxamates, pyoverdines, and carboxylates are the four primary categories" (Daly et al., 2017). "Gram-negative bacteria account for more than 90% of siderophore-producing bacterial isolates; *Enterobacter* and *Pseudomonas* are the most common. Only 2% of gram-positive bacteria, such as *Bacillus* and *Rhodococcus*, can make siderophores of the total. According to research, most rhizobacteria screened from soil or plant root tissues can stimulate plant development through siderophore synthesis if implanted into iron-deficient soils" (Tian et al., 2009). "The production of siderophores by beneficial soil/plant-related bacteria is also an essential biological control mechanism, since it competes with plant diseases for iron sources, limiting iron availability to these harmful plant pathogens" (Shanmugaiah et al., 2015).

Production of hydrogen cyanide

The synthesis of HCN is critical to the function of plant growth-boosting strains. Hydrogen in agriculture, cyanide is commonly employed as a biocontrol agent, a strategy of production based on severe toxicity against plant pathogens, metal ion chelation, and is indirectly related to the availability of phosphate(Rijavec and Lapanje 2016]. Several researchers reported that HCN-producing PGPR and its use as a biofertilizer in growth promotion tomato yield augmentation and control ailment. Many bacterial genera, including *Aeromonas, Bacillus, Pseudomonas*, and *Enterobacter* isolates HCN have been discovered to be released by tomato rhizosphere.

PGPR for nematode and insect pest control

Manipulation of beneficial organisms remains a critical strategy in an integrated pest control approach for insect pests across the world (Gangwar 2017). Although many different types of bacteria have been reported to infect insects acutely or chronically, only two genera, *Bacillus* and *Serratia*, have ever been registered to control insects.

Bacillus is the most important microbial pesticide genus. The most extensively used and successful microbial pesticide is *B. thuringiensis* (Gangwar 2017), and *fluorescent pseudomonads* have been proven to be effective against some insects and worms (Ramamoorthy et al., 2002). Youssef and Hassan (2013) revealed that "under laboratory settings, various isolates of *B. thuringiensis* and the most widely used *B. thuringiensis*-based formulations showed substantial mortality of 4th instar larvae and a considerable drop in egg hatching compared to the control". "Another study conducted in Iran discovered that bacterial isolates and protein crystals formed by B. thuringiensis during sporulation are toxic to distinct larval instars of *T. absolut*e, resulting in the target pests' quick mortality" (Ali-Rezaei and Talaei 2016). "Similarly, in greenhouse circumstances, the combination of *spinosad* and *B. thuringiensis* appears to be a viable biocontrol agent against tomato leaf miners" (Tadele and Emana 2017). "Furthermore, in greenhouse conditions, the entomopathogenic fungus *Beauveria bassiana* and *Metarhizium anisopliae* have been described as potential agents against *T. absoluta*. The most significant PGPR *fluorescent pseudomonads* enhance plant development, rhizosphere colonisation, and nematode suppression" (Tian et al., 2007). "Al-Shalaby and Sedik 2008, found that bacterial isolates of *Mycobacterium spp*., *Micrococcus* spp., *Escherichia coli, Bacillus subtilis, Serratia marcescens, Pseudomonas aeruginosa*, and *Sarcina galling* did not influence plant development when compared to the control. While Mycobacterium immunogen isolate ZHA17 boosted plant height and shoot fresh weight. Among the examined bacterial strains, ZHA296 and ZHA178of P. castaneae, as well as ZHA17 and ZHA57 of M. immunogenum, were identified as promising biocontrol agents for future nematode management strategies. *Bacillus firmus* commercial WP formulation (BioNem) was tested in Ethiopia against the root-knot nematode *M. incognita*. BioNem administered at 8 g/pot planted with a tomato seedling reduced gall development by 91%, final nematode populations by 76%, and the quantity of eggs by 45% in the greenhouse trial. As a result, plant height and biomass rose by 71% and 50%, respectively, when compared to the untreated control. BioNem applied at 200 and 400 kg ha1 was successful in lowering the number of galls (75–84%) and increasing shoot height (29–31%) and weight (20–24%) over the untreated control in field experiments. According to this study, B. firmus is a promising bacterium for the biocontrol of *M. incognita* in tomato pots" (Terefe et al.,2009). Cetintas et al.,2018 reported that the *B. pumilus* strain reduced plant root galling while increasing plant height, shoot fresh and dry weight, and root fresh weight. *Paenibacillus castaneae* isolates ZHA296 and ZHA178 decreased the quantity of egg masses and root

Stress Management

Abiotic Stress Tolerance

Aridity push, which is caused by a dry spell, salty, and high temperature, is a critical abiotic stress that limits plant efficiency and development (Vejan et al.,2016). Pseudomonas putida and Pseudomonas fluorescens, for example, can absorb cadmium from soil and may eliminate the harmful effects of cadmium pollution on grain plants, therefore they can assist manage abiotic stress utilising PGPR (Baharlouei et al. 2011). Furthermore, PGPR can enhance the amount of water available in the leaf, especially under saline and abiotic stress conditions (Naveed et al., 2014). In a few yields, including chickpea, wheat, and soybean, the foundation for the relationship between PGPR and dry season impediment has been presented (Ngumbi and Kloepper 2016). According to Habib et al., (2016), PGPR enhances the efficacy of water utilisation while increasing salty push resistance in okra via ROS-searching compounds. The improvement of leaf water status, notably under salinity and drought stress, is another prominent impact of PGPR on plants under abiotic stress conditions.

Pseudomonas aeruginosa strains boosted the development of Vigna radiata (mung bean) plants under dry circumstances, according to Sarma and Saikia (2014). Plants' capacity to use water for growth is determined by their stomatal openings. The stomata on a plant's leaf balance the amount of water in the leaf with the amount of water taken up by the roots. Under drought circumstances, Ahmad et al.2017 and Naveed et al.,2014 found that PGPR-inoculated plants had greater stomatal conductance (water vapour exiting via the stomata leaf) than non-PGPR inoculated plants The findings of both researchers show that plants injected with PGPR have a higher water-use efficiency. This discovery might be useful to the environment by eliminating excessive water consumption.

Biotic Stress Tolerance

"Biotic pressure, which is caused by a variety of diseases such as bacteria, infections, organisms, nematodes, protists, creepy crawlies, and viroids, causes a significant drop in agricultural productivity" (Haggag et al., 2015). "To comprehend such difficulties, PGPRs such as *B. amyloliquefaciens*, *B. licheniformis*, *B. subtilis*, *B. thuringiensis*, *P. favisporus*, and *P.polymyxa* might be used. Plants that are inoculated by spraying their essentials or seeds medium-term in PGPR cultures demonstrate significant resistance against various sorts of biotic pressure" (Ngumbi and Kloepper 2016).

Availability of Nutrients for Plant Uptake

“By fixing nutrients and preventing them from seeping out, PGPR can improve the availability of nutrient concentration in the rhizosphere” (Parewa et al., 2017]. “The most limiting nutrient for plants, for example, is nitrogen, which is required for the synthesis of amino acids and proteins. Prokaryotes are the only organisms that can convert atmospheric nitrogen into organic forms that can be ingested by plants” (Lioret et al., 2005; Raymond et al., 2004). Azospirillum, a rare free-living nitrogen-fixing organism that is typically linked with cereals in temperate zones and has also been shown to boost rice crop yields (Boukerma et al.,2017) is an example of a rare free-living nitrogen-fixing organism. Some PGPR has the potential to solubilize phosphate (Wani et al., 2007) resulting in enhanced phosphate ion availability in the soil that may be easily absorbed by plants. Phosphate solubilizer, IAA producer, and siderophore producer were identified in Kocuria turfanensis strain 2M4 isolated from rhizospheric soil (Jamshidnia et al., 2018).

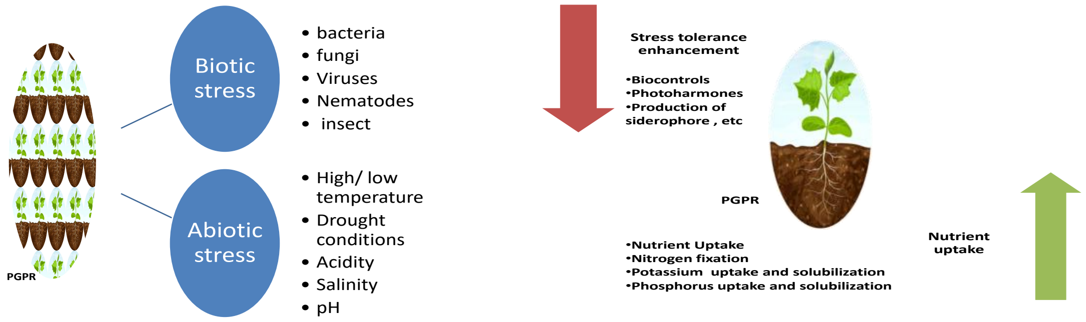
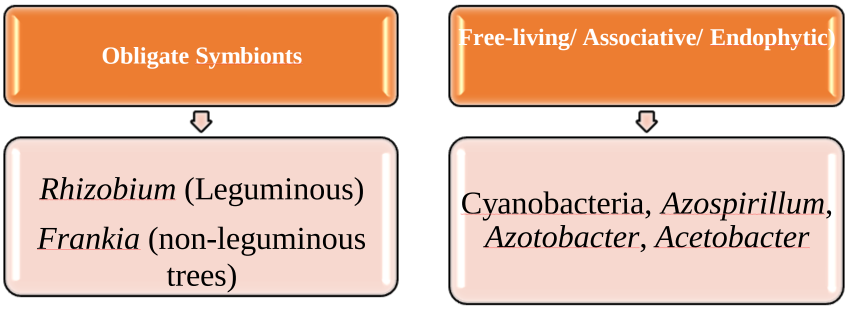


Fig 1. Nitrogen-fixing bacteria

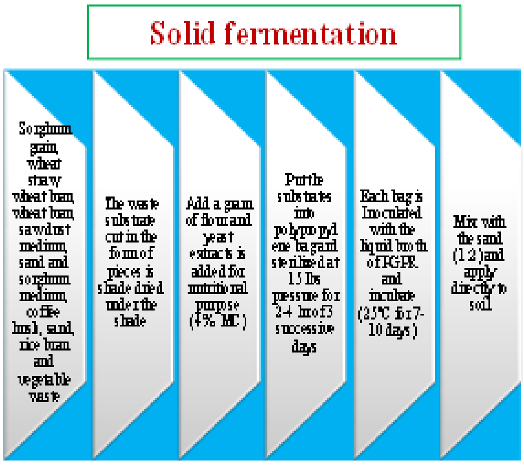
Free nitrogen (N_2) created by biological and chemical processes within the biosphere and not coupled with other elements accounts for approximately 78 per cent of the earth's atmosphere. Nitrogen is required for the development of all plants. Plants, on the other hand, cannot obtain the nitrogen they require from the atmosphere. They can only consume nitrogen that is in compound form. Nitrogen exists in the atmosphere as N_2, a form that plants cannot utilise. *Azospirillum*'s first important method for enhancing plant development is nitrogen fixation. *Azospirillum* species are aerobic heterotrophs that fix N_2 in microaerobic conditions and thrive in gramineous plant rhizospheres. The *Azospirillum*–plant relationship promotes the growth and yield of several host plants. This increase in yield is mostly due to improved root growth as a result of increased water and mineral intake, and to a lesser extent, biological N_2-fixation.

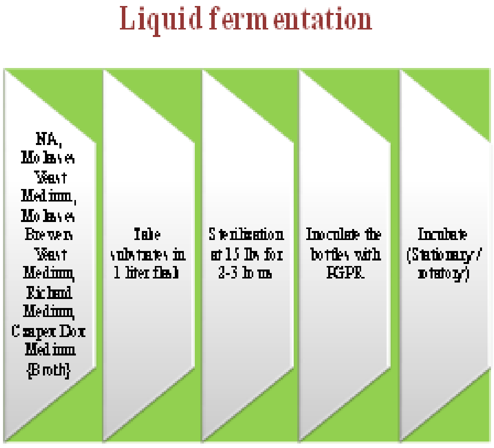
Fig 2: Obligate symbionts and endophytic bacteria



PGPR Inoculants Development and Mass Multiplication

- Solid state fermentation
- Liquid state fermentation





Carrier materials: talc powder, charcoal, peat, perlite, soil aggregates

CRITERIA FOR SELECTING AN APPROPRIATE PGPR

The rhizobacterial species should have the following properties to build an effective PGPR formulation (Jeyarajan and Nakkeeran, 2000):

- Should promote plant growth
- Should be amenable to mass multiplication
- Should have high rhizospheric competence
- Should have high competitive saprophytic ability
- Should have a broader activity spectrum
- Should be ecologically compatible with other inhabiting rhizobacteria
- Ability to tolerate abiotic (thermal, desiccation, radiations, and oxidising agents) stress

Advantages

- Long term investment
- Highly specific, easy to handle
- Eco-friendly, non-pollutant and cost-effective
- Improve soil's physical, chemical and biological properties

ConstraintsHigh cost of production

- Shelf life
- Inconsistent performance
- Sensitive to environmental conditions

Precautions and Guidelines for Using PGPRs as Biofertilizers

The following are the primary safety precautions and instructions for utilising PGPRs as biofertilizers:

(1) It is critical that the biofertilizer given for use in fields is of high quality, comprises 107 live cells per gramme as an inoculum, and is acquired exclusively from a reputable producer.

(2) Because biofertilizers are particular, they should only be applied for the crop(s) listed on the commercially available product packet.

(3) The culture bag should be labelled with the name of the crop for which it is intended.
(4) Excess culture should be injected, and any remnants/residual culture should be promptly placed in the field's grooves so that inoculum bacteria begin interacting with other microbiota in the rhizosphere and colonise it.
(5)Because biofertilizers are microbial products, they should be stored in cool, shaded settings, ideally at room temperature (25–28 C), before being applied to fields to ensure a longer shelf life.
(6) Direct contact of biofertilizers with agrochemicals (herbicides, weedicides, insecticides) should be avoided during storage or application.
(7) In general, 200 grammes of biofertilizer may efficiently treat 10 kilogrammes of seeds.
(8) Soil additions such as lime or rock phosphate are frequently recommended in adverse soil conditions, especially if the soil is extremely acidic.

Legal issues

Risk assessment and testing rules created by each country, and occasionally subnational authorities, to avoid the manufacturing and distribution of lethal/damaging organisms are one of the barriers to the proliferation and manufacture of microbe-based goods (Tabassum et al., 2017). Regulatory processes for biological or biobased goods adhere to a highly sophisticated and broad routine established by each country's regulatory and health agencies. The most time-consuming limitations for registering a biological or biobased product are the lengthy time frame, difficult documentation, and expensive fees connected with the entire product registration procedure. Since registration and regulatory regulations differ by nation, it can be difficult for enterprises to follow regulatory requirements if they wish to offer their product in different regions or countries. A product registration often necessitates national approval with certification issued by the Directorate General of Health or any other relevant regulatory entity. The product will subsequently be subjected to comprehensive and critical inspections and/or evaluations by specialists, who will be overseen by the food safety authorities and national commissions of that country or area (Basu et al., 2021). Eventually, the business will be notified of approvals and certification, allowing the manufacturers to sell their product under the certification authority's rigorous regulations and directions. Climate change is a worldwide concern, and sustainable approaches that may help to climate change mitigation should have simplified regulation and registration rules. Furthermore, governments should be flexible or adopt simpler regulations for registering and shipping indigenous and foreign microbial innovations. This may enable enterprises or PGPR developers to extend and spread PGPR-based approaches both within and outside of the nation of origin.

Future Thrust

- Microbial strains that can compete with indigenous strains and work in a variety of soil and agro-climate settings must be identified, reproduced, and made available to farmers.
- Development of suitable, less expensive, and widely available carriers for improving PGPR lifetime.
- PGPR's adaptability against harsh situations should be investigated.
- Promotional and training programmes.
- Use of nanotechnology

The Importance of Nanotechnology in Agricultural Sustainability

The use of current technologies such as nanotechnology has the potential to completely transform the agriculture economy. Nanoagriculture, which presently focuses on target farming with the use of nanosized particles such as nanofertilizer, provides unique methods for increasing agricultural plant yield through effective nutrient uptake by the plants (Tarafdar et al., 2006). The distinct physical, chemical, and biological features of nanosized particles compared to those of bigger particles have the ability to protect plants, detect plant illnesses, monitor plant development, improve food quality, boost food output, and minimise waste. Nanofertilizers outperform conventional fertilisers in terms of nitrogen loss owing to leeching, emissions, and long-term absorption by soil microorganisms (liu et al., 2006). Furthermore, Suman et al., (2010) demonstrated the benefit of employing nanofertilizers by demonstrating that controlled release fertilisers may enhance soil by reducing the negative effects associated with the overuse of regular chemical fertilizers. Conventional PGPR fertiliser application is ineffective since 90 percent is lost to the air after application, they are intolerant to the environment (heat, UV radiation, etc.), and they impact farmer application costs as run-off. Nanoencapsulation technology has the potential to be a flexible tool for protecting PGPR, increasing their service life and dispersion in fertiliser formulations, and allowing for greater flexibility.

Conclusion

Sustainable agriculture refers to the sustainable management of agricultural resources to meet evolving human requirements while preserving or improving environmental quality and conserving natural resources. New strategies should be focused on separating active biomolecules and establishing more intensive interactions between microorganisms and plants. If we can learn more about rhizosphere biology and develop any control approach for the population of soil microorganisms, future success may be easier and faster. Plants can benefit from microbial compositions while they are growing under difficult conditions. For a more successful consortium, we need much more comprehensive processes at the biochemical and molecular level to provide all of these benefits.Microbial consortia-regulated expressions of transcription factors linked to host defence responses in biotic and abiotic stressors is also missing. Rhizobacteria are bacteria that reside in the Rhizosphere area. Some of the bacteria are clinging to dirt particles. Bacterial population density is usually concentrated near the root plant, owing to the abundance of food supplies that sustain bacterium development and metabolism. PGPR increase soil characteristics by managing soil contaminations through several processes. PGPR aids in adaptation to abiotic conditions such as salinity, drought, and flood stress, as well as biotic challenges.Furthermore, PGPR aids plant adaptation to flooding stress. The rhizosphere and the PGPR rhizomicrobiome metabolize, with the former providing nutrients for the rhizomicrobes and the latter bio transforming nitrogen, phosphorus, and iron into more utilisable forms for the plants. Understanding the genetics of PGPR research and engineering it is a more promising future method that will result in over expression of the desired features in the participant strain. Because bacteria behave differently in the laboratory and in the field, it is necessary to disseminate PGPR in the field in order for them to regain their biological properties.

Future commercialization of such dried microbial inoculants, with or without the use of a carrier, might also be something to consider. Such an action can have a huge impact. Reduce the use of chemical fertilisers and encourage the use of innovative eco-agricultural techniques. However, formulation creation must take into account the product's shelf life, stability, quality, and efficacy. Because this environmentally friendly technique will be restricted by tight biosafety norms and regulations, marketing of PGPR formulations may face challenges. Rather than these, Farmers should instead focus on other contemporary methods such as frequently systematic soil analysis, the use of organic manure, optimum moisture availability, and regular sterilising measures to enhance biofertilizer performance. The government might organise technical training programmes on production techniques in partnership with research institutes and educate farmers on how to preserve the quality of PGPR formulations in the long run. Overall, widespread adoption of PGPR in sustainable farming methods has the potential to be highly successful and valuable.

Reference

Ahmed B, Zaidi A, Khan MS, Rizvi A, Saif S, Shahid M.(2017). Perspectives of plant growth promoting rhizobacteria in growth enhancement and sustainable production of tomato. Microbial strategies for vegetable production: Springer:125–49

Ali-Rezaei A, Talaei-Hassanloui R.(2016). The use of Bacillus thuringiensis-based products in biocontrol of tomato leaf miner, Tuta absoluta (*Lepidoptera*, *Lelechiidae*). *Int J Agri Innov Res*.**4**(4):814–7.

Al-Shalaby ME, Sedik M. (2008). Biocontrol activity of some bacterial isolates against Meloidogyne incognita. *Egypt J Biol Pest Control*. **18**(1):119–25.

Baharlouei J, Khavazi K, Pazira E, Solhi M. (2011). Evaluation of inoculation of plant growthpromoting rhizobacteria on cadmium and lead uptake by canola and barley. *African J Microbiol Res* .**5**(14):1747–1754

Basu A, Prasad P, Das SN, Kalam S, Sayyed R Z, Reddy MS. (2021). Plant Growth Promoting Rhizobacteria (PGPR) as green bioinoculants: recent developments, constraints, and prospects. *Sustainability* 13:140.

Boukerma L, Benchabane M, Charif A, Khelif L. (2017). Activity of plant growth promoting rhizobacteria (PGPRs) in the biocontrol of tomato fusarium wilt. *Plant Prot Sci*.**53** (2):78–

, Kusek M, Fateh SA.(2018). Effect of some plant growth-promoting rhizobacteria strains 84.

Cetintas R on root-knot nematode, *Meloidogyne incognita*, on tomatoes. *Egyptian J Biol Pest Cont*.**28**(1):1–5.

Chu BC, Garcia-Herrero A, Johanson T H, Krewulak K D, Lau CK, Peacock RS. (2010). Siderophore uptake in bacteria and the battle for iron with the host; a bird's eye view. *Biometals.* **23**: 601–611.

Daly DH, Velivelli SL, and Prestwich BD. (2017). The role of soil microbes in crop biofortification, in *Agriculturally Important Microbes for Sustainable Agriculture*, eds. V Meena, P Mishra, J Bisht and A. Pattanayak (Singapore: Springer): 333–356.

Dobbelaere S, Vanderleyden J, Okon Y. Plant growth-promoting effects of diazotrophs in the rhizosphere.(2003). *CRC Crit Rev Plant Sci* :22:107–149.

Egamberdieva D, Wirth SJ, Alqarawi AA, Allah EF, Hashem A. (2017). Phytohormones and benefcial microbes: essential components for plants to balance stress and ftness. *Front Microbiol.*:8:1–14.

Gangwar RK. (2017).Role of biological control agents in integrated pest management approaches. *Acta Sci Agri*.**1**:9–11.

Goswami D, Thakker J N, and Dhandhukia PC. (2016). Portraying mechanics of plant growth promoting rhizobacteria (PGPR): A review. *Cogent Food Agri.* 2:1127500.

Gray EJ, Smith DL. (2005) Intracellular and extracellular PGPR: commonalities and distinctions in the plant-bacterium signaling processes. *Soil Biol Biochem* 37:395–412

Habib SH, Kausar H, Saud H (2016) Plant growth promoting rhizobacteria enhance salinity stress tolerance in Okra through ROS-Scavenging enzymes. *Bio Med Res Int*:1–10

Haggag WM, Abouziena HF, Abd-El-Kreem F, Habbasha S. (2015). Agriculture biotechnology for management of multiple biotic and abiotic environmental stress in *crops. J Chem Phar.* **7**(10):882–889

Hider R C and Kong X. (2010). Chemistry and biology of siderophores. *Nat. Prod. Rep*. **27**: 637–657.

Jamshidnia A, Abdoli S, Farrokhi S, Sadeghi R. (2018). Effciency of *spinosad, Bacillus thuringiensis* and *Trichogramma brassicae* against the tomato leafminer in greenhouse. *Biocontrol*. **63**(5):619–27.

Jeyarajan R and Nakkeeran S. (2000). Exploitation of microorganisms and viruses as biocontrol agents for crop disease management, in Biocontrol Potential and its Exploitation in Sustainable Agriculture, eds RK Upadhyay, K G Mukerji and BP Chamola (Boston, MA: Springer): 95–116.

Kloepper JW, Schroth MN. (1978). Plant growth-promoting rhizobacteria on radishes. In: Proceedings of the IVth International Conference on Plant Pathogenic Bacteria: 879–882

Liu XM, Feng ZB, Zhang FD, Zhang SQ, He XS.(2006). Preparation and testing of cementing and coating nano-subnanocomposites of slow/controlled-release fertilizer. *Agric. Sci. China*.**5**:700–706.

Lloret L, Martinez-Romero E. (2005). Evolution and phylogeny of rhizobia. *Rev. Latinoam. Microbiol.* **47:**43–60.

Naveed M, Hussain MB, Zahir ZA, Mitter B, Sessitsch A. (2014).Drought stress amelioration in wheat through inoculation with Burkholderia phytofirmans strain PsJN. *Plant Growth Regul*. **73**:121–131

Ngumbi E, Kloepper J. (2016). Bacterial-mediated drought tolerance: current and future prospects. *Appl Soil Ecol*. **105**:109–125

Parewa HP, Meena VS, Jain LK, Choudhary A.(2018). Sustainable crop production and soil health management through plant growth-promoting rhizobacteria. Role of rhizospheric microbes in soil: Springer: 299–3

Patel S, Minocheherhomji FP. (2018). Plant growth promoting rhizobacteria: Blessing to agriculture. *Int J Pure Appl Biosci*. **6**:481–92

Ramamoorthy V, Raguchander T, Samiyappan R.(2002). Enhancing resistance of tomato and hot pepper to pythium diseases by seed treatment with fuorescent pseudomonads. *Eur J Plant Pathol*.**108**(5):429–41.

Raymond J, Siefert JL, Staples CR.(2004). The natural history of nitrogen fixation. *Mol. Biol. Evol.***21**:541–554.

Rezanka T, Palyzová A, and Sigler K. (2018). Isolation and identification of siderophores produced by cyanobacteria. *Folia Microbiol*. **63**: 569–579.

Rijavec T, Lapanje A. (2016) Hydrogen cyanide in the rhizosphere: Not suppressing plant pathogens, but rather regulating availability of phosphate. *Fronti Microbiol*. **7**:1–14.

Saha M, Sarkar S, Sarkar B, Sharma B K, Bhattacharjee S, and Tribedi P. (2016). Microbial siderophores and their potential applications: a review. *Environ. Sci. Pollut. Res*. **23**: 3984–3999.

Sandy, M., and Butler, A. (2009). Microbial iron acquisition: marine and terrestrial siderophores. Chem. Rev. 109, 4580–4595.

Sarma R K and Saikia RR.(2014). Alleviation of drought stress in mung bean by strain *Pseudomonas aeruginosa* GGRK21. *Plant Soils.***377**:111–126.

Shanmugaiah V, Nithya K, Harikrishnan H, Jayaprakashvel M, and Balasubramanian N. (2015). Biocontrol mechanisms of siderophores against bacterial plant pathogens. Sustain. *Approach. Control. Plant Pathog. Bacteria*. **24**: 167–190.

Singh M, Singh D, Gupta A, Pandey KD, Singh P, Kumar A.(2019). Plant growth promoting rhizobacteria: Application in biofertilizers and biocontrol of phytopathogens. PGPR amelioration in sustainable agriculture: Elsevier; 41–66.

Suman PR, Jain VK, VArman A. (2010). Role of nanomaterilas in symbiotic fungus growth enhancement. *Curr. Sci.* **99**:1189–1191.

Tabassum B, Khan A, Tariq M, Ramzan M, Khan M S I, Shahid N. (2017). Bottlenecks in commercialisation and future prospects of PGPR. *Appl. Soil Ecol.* **121**: 102–117.

Tadele S, Emana G.(2017). Entomopathogenic efect of Beauveria bassiana (bals.) and Metarrhizium anisopliae (Metschn) on Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) larvae under laboratory and glasshouse conditions in Ethiopia. *J Plant Pathol Microbiol*.**8**:1–4.

Tarafdar A., Raliya R., Wang W.N., Biswas P., Tarafdar J.C. Green synthesis of TiO_2 nanoparticle using Aspergillus tubingensis. *Adv. Sci. Eng. Med.* 2013;5:943–949.

Terefe M, Tefera T, Sakhuja P. (2009). Effect of a formulation of Bacillus frmus on root-knot nematode Meloidogyne incognita infestation and the growth of tomato plants in the greenhouse and nursery. *J Invert Pathol*.**100**(2):94–9.

Tian B, Yang J, Zhang KQ.(2007). Bacteria used in the biological control of plantparasitic nematodes: populations, mechanisms of action, and future prospects. *FEMS Microbiol Ecol*.**61**(2):197–213.

Tian F, Ding Y, Zhu H, Yao L and Du B. (2009). Genetic diversity of siderophore-producing bacteria of tobacco rhizosphere. *Brazil. J. Microbiol.* **40**: 276–284.

Vejan P, Abdullah R, Khadiran T, Ismail S, Boyce AN. (2016). Role of plant growth promoting Rhizobacteria in agricultural sustainability – a review. *Molecules*. **21**(573):1–17

Wani PA, Khan MS, Zaidi A.(2007). Synergistic effect of the inoculation with nitrogen-fixing and phosphate-solubilizing rhizobacteria on performance of field-grown chickpea. *J. Plant Nutr. Soil Sci.* **170:**283–287.

Youssef NA, Hassan GM. (2013). Bioinsecticide activity of Bacillus thuringiensis isolates on tomato borer, Tuta absoluta (Meyrick) and their molecular identifcation. *African J. Biotechnol*.**12**(23):3699–709.

Zuo Y and Zhang F. (2011). Soil and crop management strategies to prevent iron deficiency in crops. *Plant Soil*. **339**: 83–95.