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Plant Growth-Promoting Bacteria: A Catalyst for Advancing Horticulture Applications

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Endophytes which are capable of providing a plethora of beneficial effects to the plants that they inhabit are also regarded as plant growth promoting microbes. The bacteria harboured in the rhizosphere are involved in both promoting plant growth and remediating soils contaminated with pollutants like heavy metals, these microorganisms employ various mechanisms to achieve these dual objectives. PGPB is intended to stimulate the growth of plant roots (increase the root mass and/or the root capturing area), promoting nutrient uptake from the soil, and protecting plants from root diseases. PGPB contribute to heavy metal mobilization in soil through mechanisms such as solubilizing metal minerals, acidifying the rhizosphere environment, increasing root surface area for metal uptake, and enhancing the release of root exudates that facilitate metal mobilization. This Plant Growth Promoting Bacteria are called as biofertilizer which is the alternate for the chemical fertilizer and harmless for the soil, plants and consumers. In this review various applications of these bacteria are discussed and methods in which it can be beneficial to horticulture is also described.

Keywords: Biofertilizer; Gibberellins; Indole-3-acetic acid; Plant Growth Promoting microbes.

The research and application of phytotechnology using second-generation crops aligns well with the Sustainable Development Goals, particularly those relating to biomass processing for energy and bioproducts. These efforts help to mitigate climate change, promote sustainable land use, and drive innovation in bio-based industries. *Gigantic miscanthus (*M. x gigantic) is indeed a highly promising plant species with numerous beneficial characteristics[1]. It possesses a C4 photosynthetic pathway, which is more efficient than the C3 pathway found in most plants, enabling it to thrive in a wide range of environmental conditions. Additionally, M. x *gigantic* has a good environmental profile, making it an attractive option for sustainable agriculture and land use. Lead (Pb) contamination in the environment is a significant global issue, and it mainly enters the terrestrial environment through various industrial processes, including smelting, mining, processing, use, recycling, and disposal. In China, Pb is identified as the primary serious

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soil pollutant, along with other contaminants like Cadmium (Cd) and Arsenic (As), according to recent monitoring of industrial and agricultural sites.

The atmospheric deposition of Pb plays a major role in contaminating soils, surface waters, and plants. In industrialized areas, a significant portion of the lead content in plants (up to 60-70%) can come from direct atmospheric deposits. Pb pollution is prevalent in areas near industrial facilities, post-military localities, and active military localities. Pb is known to have adverse impacts on both the environment and human health. Even at low-level concentrations, exposure to Pb can lead to neurological impairment and central nervous system dysfunction. The metal does not degrade in the environment and exists in various chemical forms. Plants, including *M. x gigantic*, are affected by Pb toxicity, leading to detrimental effects from germination to yield. Higher rates of Pb exposure disrupt plant water and nutritional relations and cause oxidative damage. Studies have shown that *M. x gigantic* can exhibit stable growth in Pb-contaminated soils and soils contaminated with trace elements (TEs). However, the biomass yield tends to be lower in such soils. This has prompted research into different agricultural and microbiological practices to increase *M. x gigantic* biomass production while reducing the uptake of contaminants into the aboveground biomass[1]. The two main approaches to enhance miscanthus biomass production in trace elements' (TEs) contaminated soils involve addressing the soil conditions and influencing the rhizomes of the plant. These approaches aim to reduce the uptake and accumulation of TEs in the aboveground biomass of miscanthus, making it a more viable and safe option for biomass production in contaminated areas.

Soil-based approaches

To enhance the soil's structure and nutrient content, several soil amendments can be added, including fertilizers, sludge, and biosolids. The availability of TEs for plant uptake may be decreased while the overall health of the soil may be improved by these amendments. You can apply substances to the soil, such as citric acid and ethylenediaminetetraacetic acid (EDTA). These chelating substances join TEs to form complexes that lessen the availability of the TEs for plant uptake and their mobility in the soil. The bioavailability of TEs to plants can be decreased by certain fungi's capacity to bind with and immobilize them in the soil, such beneficial microbes can aid in this process by being added to the soil[2].

Rhizome-based approaches

Co-composting is the process of composting miscanthus rhizomes or root systems with other organic debris. This can aid in the breakdown of TEs and the reduction of their concentration in the rhizosphere, resulting in lower plant uptake. The use of particular plant growth regulators can alter the development and functionality of the root system. This can improve the plant's resistance to TE absorption and reduce translocation to aboveground biomass[2].

Introducing beneficial microbial organisms into the rhizosphere can improve the plant's tolerance to TEs. Some microbes have the capability to sequester or immobilize TEs, reducing their negative impact on the plant. Indeed, the use of microorganisms, specifically plant growth-promoting bacteria (PGPB), has gained significant attention in recent years for both plant growth promotion and the remediation of soil contaminated by trace elements (TEs). PGPB play a crucial role in facilitating the adaptation of host plants to suboptimal soil conditions, especially during stress states caused by TE contamination. The exploration of plant growth-promoting bacteria (PGPB) for revegetation and phytoaccumulation of soils contaminated with trace elements (TEs) has shown promising results in microcosm experiments. Two specific PGPB strains, *Pseudomonas sp. A3R3* and *Acinetobacter sp. SRS8*, were studied for their effects on plant biomass production and phytoremediation parameters.

The microcosm experiments revealed that the inoculation of PGPB strains, *Pseudomonas sp. A3R3, and Acinetobacter sp. SRS8*, led to several positive outcomes Both *Pseudomonas sp. A3R3 and Acinetobacter sp. SRS8* positively influenced the growth of plants. However, *Pseudomonas sp. A3R3* had a greater impact on plant biomass production, indicating its strong potential as a plant growth promoter. Influence on phytoremediation parameters: Phytoremediation is the process of using plants and associated microorganisms to clean up contaminated environments. In this case, the PGPB strains had an influence on the accumulation of elements (TEs) in plants, which is a critical aspect of phytoremediation. *Acinetobacter sp. SRS8*, in particular, seemed to play a significant role in the accumulation of elements in plants, suggesting its potential for phytoaccumulation – a process where plants immobilize and stabilize contaminants in the soil, reducing their mobility and bioavailability. The use of specific PGPB strains in phytoremediation and phytoaccumulation can be a valuable approach to enhance the overall effectiveness of revegetation efforts and mitigate the impacts of TEs on plant growth. By promoting plant growth and influencing the accumulation of TEs in plants, these PGPB strains contribute to the successful restoration and remediation of TEs-contaminated soils, making them more suitable for sustainable land use and biomass production with plants[3].

Plant growth promoting bacteria in horticulture

The emphasis on including horticultural crops in regular meals has increased as knowledge of the health-promoting qualities of phytochemicals and minerals in these crops has grown. Vegetables, fruits, spices, nuts, flowers, aesthetic plants, as well as medicinal and aromatic plants are all examples of horticultural crops. Numerous health advantages, such as a decreased risk of cancer, heart disease, infections, and other chronic diseases, have been linked to consuming these crops. The demand for fruits and vegetables has grown as the world's population rises and there is a move toward better diets. Horticulture faces difficulties meeting this increased demand for nutritious food without worsening environmental problems[3].

One of the concerns related to horticultural crop production is the significant uptake of nutrients like nitrogen (N), phosphorus (P), and potassium (K) by these crops. Under good management conditions, horticultural crops may absorb between 500 to 1000 kg of these nutrients per hectare annually or even more[3]. The excessive use of fertilizers to meet these nutrient demands can lead to several negative consequences. Absolutely, implementing more sustainable horticultural practices is crucial for achieving greater crop yield and quality while minimizing environmental impact. Emphasizing methods that improve nutrient uptake and enhance the nutrient pool in the soil can lead to more efficient resource utilization and reduced reliance on chemical fertilizers.

Microorganisms, such as *Arbuscular Mycorrhizal Fungi* (AMF) and Plant Growth-Promoting Bacteria (PGPB), offer valuable opportunities as beneficial alternatives to conventional fertilizers and chemical inputs. These microorganisms can be used as biofertilizers and bio-stimulants to improve the availability and uptake of soil nutrients by plants. They work in symbiosis with plants, enhancing nutrient acquisition and supporting overall plant health, growth, and resilience. Understanding the mechanisms by which AMF and PGPB interact with plants and the soil can provide valuable insights for sustainable horticultural production. These microorganisms offer a viable and environmentally friendly approach to improve crop productivity, reduce input costs, and promote more resilient and healthier horticultural systems[4].

Review of literature

Plant Growth Promoting Bacteria can synthesize compounds that benefit the host plant's growth and development. PGPB can help the plant in absorbing nutrients from the soil. Some PGPB can fix atmospheric nitrogen, making it available to the plant. They can solubilize minerals like phosphorus, making them more accessible to plants. PGPB produce siderophores, which solubilize and sequester iron, making it available for plant use. PGPB synthesize phytohormones like auxins, cytokinin, and gibberellins, which promote different stages of plant growth. Some PGPB synthesize enzymes that modulate plant growth and development. PGPB can induce systemic resistance (ISR), reducing the impact of harmful pathogens on plants. The protection provided by PGPB is linked to the plant's production of Jasminum ethylene. Certain PGPB can trigger the salicylic acid dependent Systemic Acquired Resistance (SAR) pathway by producing SA at the root surface[5].

PGPB in essential oil production

Essential oil production in aromatic plants is influenced by a variety of factors including physiological, biochemical, metabolic, and genetic factors. These factors are often intertwined and difficult to separate from each other. The EO production is affected by geographical location, seasonal changes, developmental stage of the plant, and even the specific organ being considered (leaves, flowers, etc.). These external factors can lead to variations in EO composition and yield. The anatomical structure of the plant, such as the presence and distribution of glandular trichomes (structures responsible for EO synthesis and storage), plays a significant role in EO production. Hormonal factors also influence EO production, with various plant growth regulators impacting both yield and quality. The presence and arrangement of glandular trichomes are often strongly correlated with the EO yield of aromatic plants. These structures are the primary sites of EO synthesis and storage. Plant growth regulators, such as methyl Jasminum, have been identified as influencers of EO production. Methyl jasmine acid, for example, plays a role in regulating the genes and enzymes involved in the biosynthesis of secondary metabolites, including terpenoids that are common components of EO[6].

Phytoremediation is an environmentally friendly and cost-effective technology that employs plants and their associated microbes to address heavy metal contamination in soil. This technology aims to extract, immobilize, or detoxify heavy metals from the soil, thereby reducing their harmful effects. In regions characterized by arid and semi-arid climates, drought is a significant concern. While certain plants have demonstrated the capability to tolerate and accumulate high levels of heavy metals, drought stress poses a challenge[5]. Drought stress can lead to severe damage to plants, limiting their growth, establishment, and overall phytoremediation efficiency. Drought stress combined with heavy metal pollution alters a series of physiological, biochemical, and molecular processes within plants. This disruption affects various aspects of plant functionality and phytoremediation potential. Drought and metal stress impact the photosynthetic efficiency of plants. This is manifested through changes in pigment concentration, disruption of photosystem ultra-structures, alterations in electron transport systems, and modifications in gas exchange mechanisms. One significant consequence of drought and metal stress is the restriction in stomatal regulation, including stomatal closure and conductance. This reduction in stomatal activity affects the availability of carbon dioxide (CO2) to chloroplasts, consequently leading to a decrease in the photosynthetic rate. This diminished photosynthetic capacity makes the plant more vulnerable to stress and its associated effects. The combination of drought and heavy metal stress creates a challenging environment for plants involved in phytoremediation efforts. The interplay between these stressors reduces the effectiveness of phytoremediation by compromising plant health, photosynthetic efficiency, and overall growth[7]. Drought and metal stress not only disrupt photosynthesis but also have a significant impact on energy conversion processes. They impede the efficiency of photosynthetic electron transport, which can lead to photoinhibition. Moreover, these stresses negatively affect the antioxidant defence mechanism within plants, resulting in the production of reactive oxygen species (ROS). ROS can cause damage to lipids, membrane permeability, and nucleic acids within plant cells. Given the adverse effects of drought and metal stress on plant health, establishment, and phytoremediation potential, there is a pressing need for efficient strategies to enhance the performance of plants in drought-prone arid and semi-arid regions.

An emerging approach to combat the challenges of multiple stresses (heavy metal pollution and drought) is the utilization of MST-PGPB. These beneficial bacteria can promote plant growth, enhance tolerance to stressors, and improve phytoremediation outcomes. MST-PGPB produce several plant growth-promoting molecules such as indole-3-acetic acid (IAA), which is an auxin hormone involved in plant growth regulation, as well as 1-aminocyclopropane-1-carboxylate deaminase (ACCD) and siderophores, which aid in stress alleviation. MST-PGPB activate antioxidant enzymes like superoxide dismutase (SOD), catalase (CAT), and phenolic compounds within plants. These enzymes help neutralize the harmful effects of ROS, reducing oxidative damage. In conclusion, the utilization of multiple stress-tolerant plant growth-promoting bacteria (MST-PGPB) presents a promising strategy to address the challenges posed by heavy metal pollution and drought stress in phytoremediation efforts. These bacteria contribute to improved plant health, stress tolerance, and overall phytoremediation efficiency by enhancing various physiological processes and promoting stress alleviation mechanisms within plants[8].

Reducing Toxicity of Heavy Metals By PGPB

Human activities, such as industrial development and various anthropogenic actions, have led to a significant increase in the contamination of both aquatic and terrestrial environments by heavy metals and xenobiotic pollutants. This pollution poses substantial risks to ecosystems and human health. Heavy metals are particularly concerning due to their toxicity and the potential for bioaccumulation. These elements can enter the food chain by being absorbed by plants through their roots, a process known as translocation. Once absorbed, heavy metals can move through the food chain and impact both plants and the organisms that consume them. PGPB are beneficial bacteria that interact with plants and promote their growth and health through various mechanisms. Some strains of PGPB possess the ability to tolerate high levels of heavy metals. Given their metal tolerance and growth-promoting properties, certain PGPB strains are utilized in bioremediation efforts. Bioremediation involves using living organisms, such as bacteria and plants, to remediate polluted environments by reducing the concentration or toxicity of pollutants. One specific application of heavy metal-tolerant PGPB is the detoxification of soils that are irrigated with heavy metal-contaminated wastewater[9]. This process helps mitigate the adverse effects of heavy metals on both the soil and the plants growing in it. As heavy metal contamination continues to rise due to ongoing industrial and anthropogenic activities, the implementation of bioremediation processes becomes a necessity. Bioremediation offers a sustainable and eco-friendly approach to addressing pollution and restoring contaminated environments. Horizontal Gene Transfer is a process through which bacteria can acquire new genes from other bacteria or even from different domains of life. This transfer of genetic material allows bacteria to incorporate advantageous genes into their genomes, enabling them to adapt to changing environments more rapidly. Horizontally acquired genes are often grouped into genomic islands. These genomic islands contain genes that are crucial for bacterial adaptation to diverse habitats. They can confer specific traits that aid in survival and proliferation in particular environments. The pan-genome refers to the complete collection of genes found across all strains of a species. It encompasses both the core genome (genes shared by all strains) and the accessory genome (genes unique to specific strains). HGT introduces substantial variability in the genes possessed by different bacterial strains of a species. Pan-genome studies involve analyse the entire gene repertoire across multiple strains. These studies provide insights into species evolution, gene function changes, and the diversity of traits within a species.

Pan-genome analysis involves examining the complete gene repertoire of a species by considering genes shared by all strains (core genes), genes shared by some strains (accessory genes), and genes unique to individual strains. Bacteria have the capacity to integrate various beneficial genes into their genomes, leading to significant intraspecific genome diversity. This diversity contributes to genetic redundancy and adaptation to diverse habitats. Accessory genes, those not shared by all strains, play a pivotal role in responding to environmental changes and contribute to adaptive evolution. Accessory genes are key drivers of bacterial adaptation. They provide the genetic flexibility necessary to respond to changing environmental conditions. By acquiring and retaining accessory genes, bacteria can adjust their capabilities to better suit the challenges of their specific ecological niches. With the advancement of next-generation sequencing technology, whole-genome sequencing has become a powerful tool. This technique enables scientists to comprehensively study the genetic makeup of organisms. Whole-genome sequencing provides in-depth insights into genetic determinants, metabolic pathways, and other molecular processes involved in various life processes and adaptations[10]. Genome annotation involves identifying and named genes and other functional elements in a genome sequence. Proteogenomic comparisons involve comparing genomic data with proteomic (protein-related) data from the same organism or related organisms. These techniques help researchers understand gene functions, protein interactions, and more. Enterobacter *OB49* is a bacterium that was isolated from wheat cultivated in soil contaminated with mixed effluents in

(*Setif, Algeria*) province. This bacterium likely possesses unique characteristics adapted to its specific environment. The study found that *OB49* demonstrated remarkable tolerance to various heavy metals, including arsenic, zinc, copper, chromium, and cadmium. This tolerance suggests that the bacterium has mechanisms to cope with and survive in a polluted environment.

Toxicological Effects of Tio_2 On PGPB

Titanium dioxide (TiO_2) is widely used in numerous consumer products across industries. It's incorporated into paints, textiles, paper, plastics, fertilizers, food items, toothpastes, cosmetics, and more. In industries like food and paints, TiO_2 is used as a whitening agent. The scattering of visible light by white TiO_2 particles results in objects appearing whiter and brighter. TiO_2 also serves as a photocatalytic antibacterial agent. Its photocatalytic properties enable it to generate reactive oxygen species (ROS) upon exposure to light. These ROS can damage microbial cell walls, leading to antibacterial effects. The antibacterial effect of TiO_2 is attributed to the production of ROS, which can harm bacterial cells. Even in the absence of light, TiO_2 has been found to inhibit bacterial growth. TiO_2 nanoparticles (NPs) are preferred over bulk TiO_2 due to their larger surface area and enhanced ability to generate ROS. This increased ROS production makes TiO_2 NPs more effective in their antibacterial and photocatalytic roles. In modern sunscreens, TiO_2 is often used in nanotech form. These nanoparticles can more effectively absorb ultraviolet rays compared to larger particles. This makes them efficient at providing protection against harmful UV radiation[11]. Titanium dioxide nanoparticles (TiO_2 NPs) are one of the most produced nanomaterials globally. The annual production in the US alone reaches up to 38,000 metric tons, and it's projected to increase significantly, potentially reaching 2.5 million metric tons by 2025. Given the widespread use of TiO_2 NPs in various consumer products, their entry into soil is expected. This entry could occur through various pathways, including runoff, deposition, and the use of biosolids as soil amendments. The total predicted environmental concentration of TiO_2 NPs in soil is estimated to be around 50 mg/kg in the European Union (EU) region. This value reflects the potential accumulation of TiO_2 NPs in soil due to their widespread use.

Combination of NPK Fertilizers And PGPB

Vegetables and their derived products, such as salads, sauces, pickled items, and dried vegetables, are rich sources of active nutraceutical ingredients. These ingredients include organic compounds, vitamins, proteins, minerals, and essential oils that are vital for human nutrition. The food industry involves complex compositions of various components, each contributing to the nutritional value of foods. The mixture of organic substances, vitamins, proteins, minerals, and essential oils in vegetables plays a crucial role in providing a balanced and nutritious diet. Vegetable production has gained significant importance in global trade due to increasing demand driven by higher income levels. This demand has led to substantial growth in vegetable production to meet the needs of consumers. Collards are a type of cruciferous vegetable and belong to the cultivar group *Brassica oleracea* variety of the species *Brassica oleracea*. This cultivar group includes other vegetables like kale and spring greens. The name "collard" is derived from the term "colewort," which refers to the wild cabbage plant[12]. Collards are mainly cultivated in various regions around the world, including Brazil, Southern United States, Portugal, different parts of Africa, Bosnia and Herzegovina, Southern Croatia, Northern Spain, and India. These areas are known for growing collards for their edible leaves. Collard leaves are large, broad, and dark blue green in colour. They have a smooth texture and are considered edible. The leaves are the primary edible part of the collard plant and hold significant nutritional value[13]. To promote environmentally friendly approaches in vegetable cultivation, biofertilizers are being explored as alternatives to traditional chemical fertilizers. In endive cultivation, partially substituting mineral NPK fertilizers with biofertilizers improves yield and agronomic qualities, resulting in healthier plants for human consumption. A combination of chicken manure and bacterial biofertilizers, such as Bacillus sp., can reduce the required amount of chemical fertilizers for crops like cucumber and pepper. This combination enhances the efficiency of nutrient utilization and reduces the environmental impact of excessive chemical fertilizer use.

Biofertilizers serve as sustainable alternatives to chemical fertilizers. They promote plant growth, enhance yield and quality of crops, and contribute to more environmentally friendly agricultural practices. By harnessing the power of beneficial microorganisms, biofertilizers aid in nutrient availability and uptake by plants. Microorganisms play a vital role in promoting nutrient circulation in the soil. They aid in nutrient cycling and transformation, making essential nutrients more available to plants. This reduces the reliance on chemical fertilizers by maximizing the natural nutrient cycling processes. In sustainable farming, organic manure is often used as a substitute for mineral fertilizers. This approach improves soil properties, enhances soil structure, retains moisture, and supports microbial activity[14]. Organic manure enriches the soil with nutrients gradually, providing long-term benefits to plant growth. Organic manure not only supplies nutrients to plants but also enhances soil properties. It improves soil structure, water-holding capacity, and aeration. Additionally, the presence of organic matter supports the growth and activity of beneficial soil microorganisms, which contribute to overall soil health. Utilizing locally produced resources, such as organic manures and other soil amendments, is an effective strategy in sustainable farming. These resources are often readily available, cost-effective, and tailored to the specific needs of the local environment. Applying eco-friendly practices like using organic manure and locally produced resources can lead to increased vegetable crop productivity. These practices promote soil fertility, nutrient availability, and overall plant health, resulting in better yields.

Rice is a crucial food crop that provides sustenance for approximately half of the world's population. It is a staple food consumed widely and is particularly important in developing and equatorial countries. Rice is known as a "thirsty crop" due to its high-water requirements for cultivation. However, it also faces challenges related to salinity stress. Despite being a halophyte (salt-sensitive plant), rice has poor physiological and molecular traits to tolerate salinity stress. Rice serves as a model plant for studying the physiological, biochemical, and molecular responses to salinity stress. Its sensitivity to salinity and the availability of genomic and molecular tools make it an ideal candidate for understanding how plants cope with salt stress. Salinity stress has multiple impacts on plant physiology, including ion imbalance, ionic toxicity, osmotic stress, reduced water potential, and disrupted growth and development[9]. Modern agriculture's heavy reliance on chemical fertilizers and pesticides is leading to changes in nutrient supply, reducing microbial diversity, and degrading soil health. This can have cascading effects on plant productivity and overall ecosystem well-being[15]. High salt concentration, characterized by increased Na^+ and $Cl^{''}$ ions in the soil, affects soil properties such as porosity, aeration, and water conductance. The accumulation of Na^+ ions in the soil can have detrimental effects on soil structure and water movement. Salinity stress deteriorates the physicochemical properties of the soil, hindering nutrient mobilization and reducing microbial diversity. This can lead to decreased nutrient availability for plants and affect overall soil health. Salinity stress suppresses the rate of photosynthesis by disrupting ion balance (Na^+ and $K^{''}$) within plants. This disruption can lead to a reduction in chlorophyll content, affecting the plant's ability to carry out photosynthesis. High ion accumulation, particularly Na^+, can induce the production of reactive oxygen species (ROS) within plants. ROS can cause damage to DNA, degrade proteins, and harm cell membranes. Increased sodium ions (Na^+) can trigger cell death and osmotic stress in plants. This impacts cell health and overall plant integrity. Salinity stress affects stomatal conductance and leaf area, which in turn hampers plant water regulation and efficiency[16].

One of the most severe abiotic factors that affects plant growth and lowers food production globally is salinity stress. According to the Food and Agriculture Organisation (FAO), up until 2019, salinity affected about 800 million acres of arable land globally. This problem is getting worse because irrigation systems are using more brackish water and low-lying coastal areas are being eroded by seawater. Recognised as a main food crop, rice provides food for close to 50% of the world's population. However, rice is particularly susceptible to salt stress in the early stages of seedling growth. Salt stress reduces plant development and photosynthesis, which lowers the overall production of rice. Additionally, salt stress not only impairs hormonal balance and decreases nutrient mobilisation[16]. An important factor in improving crops' tolerance to salinity stress is the presence of salt-tolerant plant growth-promoting bacteria (PGPB). One of the most crucial characteristics for boosting the growth of salt-stressed plants with PGPB is the creation of 1-aminocyclopropane-1-carboxylate (ACC) deaminase enzyme. The ACC enzyme hydrolase the ACC, a precursor to ethylene, to produce ammonia and -keto acid. Additionally, PGPB could generate indole acetic acid (IAA) to encourage lateral root formation in Arabidopsis thaliana a salt stress state. TY0307, a PGPB isolated from paddy soil that can withstand salt, may efficiently increase rice growth by causing proline and generating IAA even at high salt concentrations, build up. The variety of microbial communities in the soil and the activity of soil enzymes can both be impacted by salinity. the Bacillus vaccination.

PGPB and compost provide necessary nutrients in mining tailing sites

Mining tailings sites in arid and semi-arid environments often lack vegetation due to factors like metal toxicity, acidic pH, poor soil structure, low nutrient levels, and stressed microbial communities. Compost helps reduce bulk density, increase pH, mitigate metal toxicity, retain water, and provide necessary nutrients. Compost addition can improve the soil's physical and chemical properties, making it more suitable for plant growth. In sites with high contamination levels (high metal content, low pH), a significant amount of compost material may be required to establish vegetation. This can increase the cost of remediation efforts. PGPB have been widely used in agriculture to enhance plant growth by promoting various mechanisms. These bacteria can also play a role in environmental applications, such as remediating mining tailings sites. PGPB can be applied to seeds before planting, leading to improved plant growth even at lower-than-optimal compost rates. This approach can result in resource and cost savings while aiding in vegetation establishment[17]. In previous studies, seeds were often prepared for inoculation by surface sterilization to give the introduced PGPB strains a competitive advantage in colonizing the seed surface. However, this step can add complexity to the inoculation process and might have potential negative effects on plant germination. The immersion method involves soaking seeds in PGPB suspensions shortly before planting. This method is relatively straightforward but requires the PGPB to be prepared and applied immediately before planting. It might be challenging for larger-scale applications due to the need for timely preparation. Alginate encapsulation is another approach to introduce PGPB to seeds. In this method, PGPB are coated with alginate beads, which can be lyophilized (freeze-dried) and stored for extended periods without losing viability. Alginate beads act as a protective coating that slowly disintegrates, releasing the PGPB as the plant germinates. The choice between immersion and alginate encapsulation methods depends on the specific goals, scale, and logistical requirements of the project. Alginate encapsulation's ability to store PGPB for extended periods and its controlled release feature make it an attractive option for larger-scale applications and commercial use[18].

The rhizosphere, the soil surrounding plant roots, is a dynamic and complex environment populated by a diverse microbial community that supports plant establishment. During phytoremediation, which involves using plants to stabilize contaminated soils, significant changes in the rhizosphere microbial community occur even in the absence of PGPB. Prior to plant establishment, arid tailings sites with high metal content and acidic conditions may have a microbial community dominated by acidophilic iron- and sulphur-oxidizing bacteria. These conditions are often not conducive to plant growth. Upon the establishment of plants in these challenging environments, significant shifts in the microbial community structure are observed. The numbers of different microbial groups can change dramatically. Neutrophilic heterotrophs, which are generally more same for plant growth, increase in number[19]. Meanwhile, populations of iron and sulphur oxidizers, which are less beneficial for plants, decrease. While PGPB have been widely used in agriculture to promote plant growth through mechanisms like siderophore and plant hormone production, there is limited information available about how PGPB influence the development of the rhizosphere microbial community beyond these specific activities. The exact role of PGPB in shaping the rhizosphere microbial community structure remains relatively unexplored. Although

PGPB are known to interact with plants and influence their growth, their broader impacts on microbial diversity, composition, and interactions in the rhizosphere are not well understood.

Plant-associated microorganisms, particularly PGPR, have a significant role in both promoting plant growth and remediating soils contaminated with pollutants like heavy metals. These microorganisms employ various mechanisms to achieve these dual objectives. PGPR contribute to heavy metal mobilization in soil through mechanisms such as solubilizing metal minerals, acidifying the rhizosphere environment, increasing root surface area for metal uptake, and enhancing the release of root exudates that facilitate metal mobilization. Phytohormone Production of phytohormones like indole-3-acetic acid (IAA) and gibberellins (GA3) can promote heavy metal tolerance. Salicylic acid has positive effects on maintaining and enhancing heavy metal tolerance. Proline accumulation helps plants cope with heavy metal-induced stress. Exopolysaccharides contribute to heavy metal tolerance by forming protective layers around root tissues. These compounds can chelate heavy metals, making them less available for uptake by plants. While plants require certain essential metals for growth, excessive amounts of these metals can be toxic. When concentrations surpass optimal levels, toxic heavy metals can directly inhibit enzymatic functioning, disrupt nucleic acid structure, interfere with nutrient uptake and distribution, and cause imbalances in essential nutrients. Heavy metal pollution poses a serious environmental threat, contaminating the food supply, especially vegetables. These metals can enter the food chain and impact human health. Moreover, heavy metals induce oxidative stress by generating reactive oxygen species (ROS), damaging cells and weakening their inherent defence mechanisms.

PGPB synthesize the phytohormone to improve the plant growth

The challenge of feeding a rapidly growing global population in a sustainable manner has gained significant attention. The use of chemical fertilizers to increase crop productivity has increased alongside population growth. However, the negative impacts of excessive chemical fertilizer use on human and environmental health have highlighted the need for alternative approaches. To address the sustainability challenge, there is a focus on harnessing the intrinsic biological potential of soil ecosystems. This approach aims to utilize the natural interactions and processes occurring within soil to enhance crop growth and productivity. PGPB have emerged as a promising solution to replace conventional agricultural practices, including heavy reliance on chemical fertilization and controlling pathogenic agents. PGPB offer a more sustainable approach by leveraging their positive effects on plant growth and soil health. PGPB influence both abiotic (non-living) and biotic (living) mechanisms within soil and plant ecosystems. Their activities can impact nutrient availability, root development, and overall plant growth[14]. PGPB can directly and indirectly influence plant growth and root development through various activities. These activities may occur individually or synergistically to improve nutrient acquisition and other growth-related processes. One of the notable effects of PGPB is their influence on nutrient uptake by plants. PGPB can enhance the availability of nutrients in the *rhizosphere* (root zone) and promote biochemical processes that improve nutrient uptake by plant roots. PGPB can facilitate the uptake of specific nutrients such as nitrogen (N), potassium (K), and iron (Fe). They achieve this through processes like nitrogen fixation, solubilization of immobilized forms, and enhancing the availability of essential nutrients. Iron (Fe) uptake is particularly significant for crop productivity, alongside other key nutrients like phosphorus (P) and nitrogen (N). PGPB can play a role in improving iron uptake by plants, which is crucial for various biochemical processes.

In soil, the content of phosphorus (P) is abundant, but the form that plants can readily absorb, monobasic H2PO4 (Pi), can become less available due to precipitation with other ions in different soil types. PGPB contribute to P supply to plants by solubilizing and mobilizing inorganic and organic P. They achieve this by releasing organic acids that facilitate ligand exchange reactions and producing phosphatase enzymes that break down organic P compounds. PGPB possess metabolic pathways for synthesizing phytohormone, such as indole-3-acetic acid (IAA), cytokinins (CKs), gibberellins (GAs), and ethylene (ET*)* [14]. These phytohormone have a significant impact on various morphogenetic processes in plants, including cell elongation, division, root development, and tissue differentiation. IAA, a type of auxin, is a plant hormone that plays a crucial role in multiple plant processes. It promotes cell elongation and division, influences apical dominance, aids in root development, contributes to the formation of vascular tissue, triggers ethylene biosynthesis, and influences phototropism (growth towards light). PGPB producing IAA can influence root development and morphology. The application of exogenous IAA to plants has been shown to enhance the activity of ferric-chelate reductase (FCR), an enzyme involved in the reduction of Fe3 to Fe2 at the plasmalemma. This reduction-based mechanism is crucial for the uptake of iron (Fe) in dicot plants. IAA's role in enhancing FCR activity can improve Fe uptake and contribute to overall plant health.

The success of metal phytoextraction can be hampered by various factors, including soil properties and the metal accumulation capacity of plants. Soil characteristics like pH, organic matter content, and mineral composition can influence the availability and mobility of heavy metals, affecting their uptake by plants. Additionally, some plant species may not have the necessary metal-accumulating capacity to efficiently remediate highly contaminated soils. The interactions between

Table 1. Endophytes and their beneficial roles

Endophytic Bacteria	Functions and applications
Bacillus, Pseudomonas, Streptomyces	Synthesis of pyoluteorin, phenazines and other bioactives to ward off pathogens[35, 36]
Bradyrhizobium, Azospirillum, Azocarcus,Azotobacter	Nitrogen fixation[37]
Phosphate solubilizing bacteria - Bacillus, Pseudomonas, Micrococcus	Phosphorus production[38]
Pseudomonas spp., Lactobacillus, Bacillus cereus, B. subtilis, Gluconacetobacter, Azospirillum	Production of phytohormones [39, 40]
Paenibacillus spp., Bacillus spp., Streptomyces griseus	Bioremediation[41, 42]

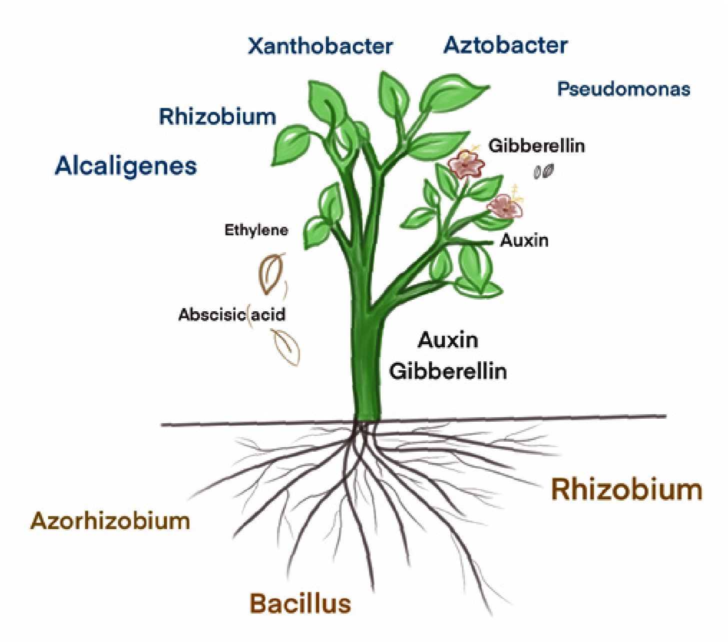

Fig. 1. Phytohormones' functions and synthesizing bacteria

metals, *rhizosphere* microbes (microorganisms present in the root zone), and plants have gained attention as potential tools for enhancing phytoremediation strategies. Microorganisms play a crucial role in the biogeochemical cycling of metals in the *rhizosphere*. They can directly contribute to metal removal from polluted soils through processes such as bioaccumulation, biosorption, and intracellular metal sequestration[15.] The *rhizosphere*, the soil zone surrounding plant roots, is a dynamic microenvironment where intricate interactions between roots, microbes, and soil occur. Microorganisms that inhabit the rhizosphere can have a significant impact on plant health, growth, and metal uptake. These microorganisms can form communities that aid in promoting plant growth and detoxifying hazardous waste compounds. Certain metal-resistant microorganisms have biotechnological potential for assisting in metal remediation. They can influence trace metal mobility and availability to plants by releasing chelating agents that bind to metals, altering soil pH through acidification, solubilizing phosphate to enhance nutrient uptake, and facilitating redox changes that affect metal speciation and mobility. Microorganisms, especially plant growth-promoting bacteria (PGPB), can directly impact metal uptake and accumulation in plants. PGPB can enhance metal tolerance in plants by producing metabolites like phytohormones, siderophores, and organic acids that influence metal availability and uptake. They can also improve plant growth by promoting root development and enhancing nutrient uptake, indirectly contributing to metal phytoextraction potential[16].

Metalliferous mine tailings are a significant environmental concern due to the presence of metals and associated contaminants. These contaminants can spread through dust or leach into nearby water bodies, posing risks to both ecosystems and human health. Traditional remediation techniques for tailings involve chemical and physical methods, but these can be costly and may not always provide sustainable solutions. Phytoremediation, the establishment of vegetation on mine tailings to stabilize the site and prevent further contamination, is an attractive option due to its simplicity and relatively lower cost compared to other methods. However, the high metal concentrations and nutrient deficiencies in mine tailings can hinder plant growth and establishment, leading to slow growth rates and limited success in Phytoremediation efforts. Plant growth-promoting bacteria (PGPB) have emerged as potential allies in Phytoremediation efforts. PGPB are capable of mitigating the challenges posed by high metal concentrations and nutrient deficiencies in mine tailings[16]. They can promote plant growth by various mechanisms, such as nutrient solubilization, hormone production, and facilitation of nutrient uptake by plants. PGPB can also enhance the tolerance of plants to heavy metals by stimulating defence mechanisms and reducing metal uptake. Numerous studies have highlighted the positive effects of PGPB inoculation on plant growth and rhizosphere community structure in metalliferous mine tailings. By improving plant growth and establishment, PGPB contribute to the success of Phytoremediation efforts. Additionally, PGPB can reduce or eliminate the need for additional fertilization, making the Phytoremediation process more cost-effective. As research on the role of PGPB in mine tailing remediation continues to grow, there is increasing interest in harnessing the potential of these microorganisms to improve the efficiency and sustainability of Phytoremediation projects. By enhancing plant growth, nutrient availability, and metal tolerance, PGPB offer a promising avenue for overcoming the challenges associated with mine tailings and promoting the establishment of healthy vegetative covers in these degraded environments[17].

Tomatoes are highly popular and widely cultivated vegetables globally. Organic production of tomatoes is valued for promoting human health by reducing exposure to synthetic pesticides and chemical fertilizers, thus enhancing food safety. Organic farming practices emphasize natural methods to enhance soil health, maintain biodiversity, and minimize negative environmental impacts. Transition from conventional to organic farming involves a period of adjustment and learning for farmers. This transition aims to replace synthetic inputs with organic practices while maintaining or improving crop yields and soil health. However, during the transition period, there might be a temporary reduction in production due to the adjustment of farming practices and the time it takes for soil health and nutrient cycling to improve[18]. Vermicomposting involves the breakdown of organic materials (such as kitchen waste, agricultural residues, and plant trimmings) through the digestive processes of earthworms and the microbial communities associated with them. Vermicompost has been found to be an effective substitute for peat in greenhouse tomato production. Peat is commonly used as a growing medium due to its water-holding capacity and structure. Vermicompost contains a diverse array of beneficial microorganisms that contribute to nutrient cycling and disease suppression in the soil. Vermicompost is known for its ability to promote plant growth, particularly in root systems.

Humic acid and PGPB significant impact in maize growth

Humic acid substances are organic compounds derived from the decomposition of plant and animal matter. They are known to have positive effects on soil structure, nutrient availability, and microbial activity. Plant growth-promoting bacteria (PGPB) are beneficial microorganisms that enhance plant growth through various mechanisms, such as nutrient solubilization, hormone production, and disease suppression. The review highlights the potential benefits of combining humic acid substances and PGPB in agricultural practices. This combination is shown to have synergistic effects on crop growth and productivity[18 19]. The interaction between humic acid substances and PGPB can enhance the overall effectiveness of plant growth promotion strategies. In their research, Canellas and Olivares demonstrated the suitability of using humic acid as an adjuvant in bacterial foliar sprays. Foliar application involves spraying solutions directly onto the leaves of plants. They found that the combined application of humic acid and PGPB had significant positive impacts on maize growth under field conditions. The research findings showed that maize grain productivity was substantially increased by the combined application of humic acid and PGPB. The increase in grain productivity was 65% higher compared to untreated controls. Furthermore, the combination of humic acid and PGPB outperformed fields treated with either humic acid or PGPB alone, demonstrating the potential synergy between these two components[20].

MHB and PGPB exhibits differential growth responses when planted in forest soil

Land degradation caused by human activities has led to the transformation of once-arable lands into areas unsuitable for agriculture. While various techniques such as hydrologic, agronomic, and biological methods can be employed to remediate degraded lands, these approaches often require substantial resources, time, and societal support. Afforestation, which involves planting trees to restore ecosystems, is a promising strategy for rehabilitating degraded areas. To further enhance the success of afforestation efforts, the introduction of appropriate rhizosphere microbes can aid in the establishment of plants. Ectomycorrhizal fungi (ECM) play a crucial role in the symbiotic associations with most forest trees[21]. They significantly contribute to plant development by improving nutrient uptake and water availability while also contributing to soil structure. However, the establishment and effectiveness of mycorrhizal associations are heavily influenced by the composition of the soil microbial community, especially in the rhizosphere. Plant growth-promoting bacteria (PGPB) constitute a diverse group of microorganisms that naturally associate with plants and have the potential to enhance plant growth. Among these, mycorrhization helper bacteria (MHB) are a specific subset that aid in promoting fungal expansion and facilitating mycorrhization. They achieve this by stimulating the growth of fungal hyphae or assisting in the formation of mycorrhizal associations. Interestingly, while MHB and PGPB are categorized separately, there is often an overlap between the two groups. Some bacteria, such as Pseudomonas and Bacillus, can belong to both categories, having the ability to promote plant growth and enhance mycorrhizal associations simultaneously.

The utilization of microorganisms to facilitate afforestation on degraded soils, especially when combining the beneficial effects of both bacteria and fungi, holds significant promise. The synergistic advantages of using mixed inoculant have been emphasized by numerous researchers, particularly in situations where the environmental conditions might not be conducive for the fungi alone. However, the effectiveness of such combined approaches may vary depending on the specific context, and further studies are essential to comprehend the potential synergies under diverse scenarios. The primary objectives of this study were to compare the growth performance of Betula pre-adult (downy birch) in forest soil versus highly alkaline anthropogenic sediment and to assess the impact of inoculation with brown roll-rim (a mycorrhizal fungus) and sp. (a bacterial species), both individually and in combination. The study aimed to address questions such as whether Betula brown roll-rim would exhibit differential growth responses when planted in forest soil compared to alkaline anthropogenic sediment, and how the inoculation with specific microorganisms, either fungi or bacteria, or a combination thereof, might influence the growth and establishment of the birch trees in these contrasting soil types. This investigation could shed light on the potential benefits of using microbial inoculants to improve tree growth in challenging environments and offer insights into the synergistic effects of using both bacteria and fungi together.

PNSB utilized as PGPB

The projection indicates that due to the expected expansion of exports to markets outside the European Union, Thailand's total chicken meat exports are anticipated to experience a 6% increase, reaching 870,000 metric tons in the year 2019. However, the extensive processing of poultry, which involves significant water usage, gives rise to challenges related to the management of slaughterhouse wastewater[22]. This wastewater contains substantial amounts of organic substances, including suspended solids, soluble organic compounds, as well as essential plant nutrients such as nitrogen and phosphorus. Proper treatment of this wastewater is crucial to ensure that the treated effluent meets the required discharge standards and prevents any adverse environmental impacts. One promising approach for treating such wastewater involves the utilization of purple non-sulphur bacteria (PNSB). Research has extensively explored the activity of PNSB across different types of wastewaters. These bacteria demonstrate versatility in their growth, functioning either as phototrophs or heterotrophs depending on the prevailing environmental conditions. In their phototrophic mode, they harness sunlight during the light-dark cycle, especially under anaerobic or microaerobic condition. PNSB can utilize organic compounds for growth in their photo-organotrophic mode or CO_2 in their photo-autotrophic mode. Furthermore, PNSB can utilize sulphur in reduced forms like sulphide obtained from hydrogen sulphide (H_2S) or thiosulfate as electron donors for photosynthesis. To support their growth, aeration is necessary, particularly at night, to enable their fermentative metabolism under aerobic dark condition[23].

PGPB treated in drought tolerance, global climatic conditions and water scarcity

Predictions from environmental studies indicate that the frequency and severity of drought events are expected to increase in the coming years due to global climate changes. Drought, characterized by water scarcity, is a significant abiotic stress that has had a substantial negative impact on agricultural productivity on a large scale. This phenomenon is particularly evident in regions like the Brazilian semiarid, where irregular rainfall distribution and alterations in water patterns contribute to reduced crop yields. Maize is a prominent crop grown in this region, serving as a subsistence crop and holding a significant position in the global cereal market[24]. Given the challenges posed by water scarcity, the utilization of drought-tolerant microorganisms presents a promising strategy to enhance crop growth and development, especially in areas with limited water availability. This approach involves the exploration and identification of specific bacteria that thrive under water stress conditions, ultimately supporting plant adaptation to such challenging environments. Prospecting for bacteria that can withstand and even thrive under water stress conditions holds potential benefits for agriculture. By selecting and utilizing these microorganisms, it may be possible to enhance the ability of plants to cope with drought-induced stress, ultimately contributing to improved crop yields, even in regions characterized by low water availability.

The Brazilian tropical semiarid region is known for its high temperatures, significant variations in rainfall distribution (averaging between 250 to 800 mm), and prolonged periods of drought. This area is home to a unique type of deciduous forest known as the Caatinga. The Caatinga is dominated by xerophytic vegetation, consisting of various plant families, with prominent representation from Cactus, Fabaceae, and Spurge.

The soil and plant microbiome of the Caatinga region also showcase remarkable biodiversity and biotechnological potential[24]. Despite the challenging conditions, temporary ponds are a common feature in the Northeastern Brazilian semiarid landscape. These ponds are typically small natural wetlands that undergo cycles of flooding and drainage. Despite often drying up completely during the dry season, they are ecologically essential in maintaining biodiversity. A plant species well-adapted to these temporary ponds is mimosa (Acacia), a member of the Fabaceae family. Overall, the unique ecological features of the Brazilian semiarid region, including its distinctive vegetation and temporary ponds, provide valuable insights into how life thrives in harsh environments and highlights the importance of biodiversity for ecosystem resilience.

Indeed, the unique ecological conditions of temporary ponds in the Brazilian semiarid region, such as those inhabited by the mimosa plant (acacia), offer a rich reservoir of microorganisms with valuable biotechnological potential. Among these microorganisms, plant growth-promoting bacteria (PGPBs) stand out for their ability to not only promote plant growth but also to enhance plant resilience to water deficit, a critical challenge in such environments. PGPBs associated with this tree can play a significant role in enhancing plant growth and survival by employing various mechanisms. One of these mechanisms involves the production of indole-3-acetic acid (IAA), a plant hormone that stimulates root growth and development. Additionally, these bacteria are capable of solubilizing phosphate, making it more available for plant uptake, and performing biological nitrogen fixation, thus contributing to improved nutrient availability for the host plant. Another remarkable aspect is the ability of these PGPBs to induce drought tolerance in plants through a process known as systemic induced tolerance. This involves triggering a series of physiological and biochemical changes in the plant. For example, the enzyme ACC deaminase, produced by these bacteria, can decrease the plant's ethylene levels, leading to reduced stress responses[25]. The formation of biofilms by PGPBs can help protect plant roots from desiccation and enhance nutrient uptake efficiency. Production of exopolysaccharides contributes to maintaining water availability in the rhizosphere, and osmotic adjustment helps plants maintain their water balance under drought conditions. By harnessing these mechanisms, PGPBs associated with mariposa plants offer a biotechnological approach to improving plant growth and survival in water-limited environments. Their ability to enhance nutrient availability, stimulate root growth, and confer drought tolerance highlights their potential to contribute to sustainable agriculture and ecosystem restoration efforts in the semiarid regions.

Indeed, the rhizobacterium Spirillum stands out as a significant model organism among plant growth-promoting bacteria (PGPB). Its role in promoting plant growth has been extensively studied, particularly the species Spirillum assimilation, which has demonstrated beneficial effects on various plants, including maize and wheat. One of the key features of Spirillum assimilation is its ability to induce changes in plant root architecture. This bacterium can influence the development of lateral and adventitious roots in several plant species. When inoculated, it promotes the proliferation of plant roots, leading to increased root surface area and enhanced nutrient and water uptake. The interaction between Spirillum and plant roots is crucial for its growth-promoting effects. The bacterium colonizes the surface of the plant roots[26], forming a beneficial association. This colonization triggers various mechanisms that contribute to enhanced plant growth. One significant mechanism is the production of auxins, which are plant hormones that stimulate root growth and development. This results in increased root exudation, which provides nutrients and organic compounds that can further enhance soil microbial activity and nutrient availability. While the exact mechanisms of how Spirillum promotes the plant, growth are not fully understood, several factors have been proposed. Phytohormone production, particularly auxins, is a key factor. Additionally, some strains of Spirillum are capable of biological nitrogen fixation, which can provide plants with an additional source of nitrogen, an essential nutrient for growth.

Comparative studies of rhizobium, brady rhizobium

Groundnut appears that you've provided information about groundnut, also known as peanuts (Arachis hypogaea L.), emphasizing its significance as a food legume in tropical and subtropical regions. The text mentions that groundnut is cultivated in 94 countries across various agro-climatic conditions. Notably, it thrives in poorly fertile and rainfed conditions, possibly explaining variations in yields among countries. The mention of countries like India and Nigeria having lower yields compared to Brazil or Argentina despite larger cultivation areas suggests that environmental and agricultural practices might play a role in these differences[27]. Furthermore, the text highlights the nitrogen (N) requirements of groundnut, which are higher (150-200 kg ha^{-1}) than cereals due to its high protein content. Despite this, groundnut can fulfil a significant portion (60-80%) of its nitrogen needs through symbiotic nitrogen fixation via root nodules. This ability reduces its dependence on soil nitrogen (20-40%), influencing overall yield. Overall, the provided information sheds light on the global importance of groundnut, its adaptability to diverse conditions, and the unique aspect of nitrogen fixation contributing to its growth.

The Rhizobium, a Gram-negative nitrogen-fixing soil bacterium, on legumes, specifically groundnut. The inoculation of three groundnut varieties with the industrial strain CIAM0104 Bradyrhizobium sp. (Arachis) has been shown to increase various growth parameters and yield. Specifically, the studies indicate that the inoculation with this strain led to an increase in dry mass of plants, 1000 seeds, seed yield, and the total number of nodules. Another study by demonstrated the positive effects of groundnut seeds coated with three Bradyrhizobium strains (AHR-2, AHR-5, and AHR-6)[27]. The coated seeds exhibited significantly enhanced germination, higher seedling biomass (80-90% increases), increased nodule number (more than a three-fold increase), higher nodule fresh weight (up to a 10-fold increase), and greater average nodule weight (about a three-fold increase) compared to uninoculated control seeds. These findings suggest that the inoculation of groundnut with specific strains of Bradyrhizobium can improve various aspects of plant growth and productivity, providing potential benefits such as increased seed yield and enhanced germination rates while potentially reducing production costs[28].

Role of PGPB in the contaminated soil

Pollutants like heavy metals (HMs) and metalloids (Ms) can significantly influence the interaction between plants and microorganisms. The extent of contamination often shapes the composition and structure of bacterial communities, which in turn impacts their ecological functions within the ecosystem. Studies have demonstrated that certain metal-tolerant plant growth-promoting bacteria (PGPBs) have the ability to confer substantial protection to plants against the toxicity of heavy metals[29]. These PGPBs can enhance plant growth and contribute to the effectiveness of bio phytoremediation, even in cases involving challenging contaminants like arsenic (As). Additionally, these plants should be capable of producing a significant biomass, as the effectiveness of phytoremediation is often proportional to the amount of biomass produced. Preferably, the chosen plant species should also be native or autochthonous to the region, as they are more likely to thrive and adapt well to the local conditions. In essence, the success of phytoremediation is contingent on a mutual compatibility between metal-tolerant microorganisms and pollutant-tolerant plants. This collaborative approach harnesses the natural abilities of both microorganisms and plants to remediate polluted sites effectively, contributing to the restoration of contaminated ecosystems.

Application studies

Purple non-sulphur bacteria (PNSB) exhibit a versatile range of metabolic pathways that offer several advantages when applied in wastewater treatment. For instance, their utilization in wastewater treatment under light conditions has been shown to mitigate the foul smell of hydrogen sulphide (H_2S) in various types of wastewater, such as rubber sheet wastewater in lagoons or anaerobic treatment ponds. Additionally, this treatment process yields single-cell protein (SCP) biomass. PNSB biomass is rich in protein, essential amino acids, photopigments, and vitamins, making it a valuable resource for single-cell protein production. Notably, PNSB are not only nitrogen-fixing bacteria but also function as plant growth-promoting bacteria (PGPB), releasing plant growth-promoting substances (PGPS) such as 5-aminolevulinic acid (ALA)[30]. They have shown potential as biofertilizers or PGPB, promoting rice growth and yield while concurrently reducing methane (CH_4) and carbon dioxide (CO_2) emissions both in laboratory settings and paddy fields. Moreover, the deceased cells of PNSB are considered to be richer sources of essential plant nutrients—nitrogen (N), phosphorus (P), and potassium (K)—compared to microalgae. This aspect, particularly the high content of phosphorus, can contribute to soil quality enhancement and stimulation of plant growth. Despite these advantages, there is currently no research investigating the use of PNSB for treating chicken slaughterhouse wastewater (CSW). Numerous studies have explored various physicochemical and biological systems for CSW treatment.

Therefore, it is worth exploring the potential of using PNSB to treat CSW while harnessing the beneficial by-products for agricultural purposes, such as promoting plant growth. When applying PNSB in wastewater bioaugmentation, factors like inoculum size and physiological conditions related to the environment need to be considered. Initial pH is a critical parameter for cell proliferation, and light intensity plays a significant role in supporting PNSB growth in phototrophic mode. To enhance treatment efficiency, providing optimal light intensity during the night is crucial. PNSB prefers phototrophic growth conditions over heterotrophic conditions[31]. Given these complexities, optimization of factors like inoculum size, pH, and light intensity is essential when using PNSB for CSW treatment. Response surface methodology (RSM), a statistical technique, can be employed to identify the influence of multiple independent variables and identify an operating region that satisfies treatment specifications while maximizing the stimulation effect.

The Rhizobia as efficient bacterial symbionts of legumes, particularly in the process of biological nitrogen fixation (BNF). Rhizobia have the ability to metabolize atmospheric nitrogen and convert it into a plant-usable form within specialized structures called nodules. These nodules maintain aerobic conditions through leghaemoglobin, a protein that helps in nitrogen fixation. In this symbiotic relationship, the legume plants provide carbon substrates derived from photosynthesis to the Rhizobia, and in return, the Rhizobia contribute by fixing atmospheric nitrogen, making it available to the plant[32]. This mutualistic association is critical in agriculture, as approximately 80% of biologically fixed nitrogen in agriculture comes from symbiosis involving leguminous plants and Rhizobiaceae bacteria. Moreover, the benefits of biological nitrogen fixation extend beyond the host crop. The fixed nitrogen in the soil benefits subsequent crops in the same field. Additionally, Rhizobia can act as non-symbiotic plant growth-promoting bacteria (PGPB) in certain non-legume crops like rice or wheat. These non-legume crops can also derive advantages from Rhizobia as endophytes, showcasing the broader positive impact of Rhizobia in agricultural ecosystems.

The diverse functional categories of polysaccharides produced by microorganisms play a crucial role in adapting to extreme environmental conditions. These polysaccharides, including intracellular polysaccharides, structural polysaccharides, and extracellular polysaccharides or exopolysaccharides (EPS), have found applications in various industrial fields. The physical and chemical characteristics of EPS, determined by the composition of individual monomers and non-carbohydrate components, make them versatile for use in different applications. Bacterial EPSs serve as effective bio emulsifiers, efficiently emulsifying substances like vegetable oils and aromatic hydrocarbons. This property is valuable in industries requiring emulsification processes, such as food and cosmetic manufacturing. EPS can assist in the sorption of exogenous organic compounds, making them useful in bioremediation processes. This involves the removal or degradation of pollutants from the environment[33]. Certain bacterial EPS, such as welan, xanthan, and gellan, act as rheology modifiers in aqueous systems. They influence the flow and deformation characteristics of these systems, making them applicable in industries like food, pharmaceuticals, and cosmetics. Some EPS, like bacterial cellulose, contribute to the development of biomaterials. Bacterial cellulose has unique properties that make it suitable for medical applications, including wound dressings and tissue engineering. EPS can bind to heavy metals, aiding in their sorption to bacterial cells. This property is valuable in bioremediation efforts aimed at removing heavy metals from contaminated environments. Bacterial EPSs can be employed as carriers for drug delivery. Their biocompatibility and controlled release properties make them suitable for use in pharmaceutical applications[34]

CONCLUSION

The use of Plant Growth-Promoting Bacteria (PGPB) is a promising approach for sustainable agriculture and improving crop productivity. PGPB have a positive impact on various aspects of plant growth, including nutrient uptake, stress tolerance, and disease resistance. The benefits of PGPB include increased crop yields, improved soil fertility, and reduced reliance on synthetic fertilizers and chemical pesticides. The compatibility of PGPB with diverse crop species suggests their potential for widespread application across different agroecosystems. However, challenges such as optimizing formulations, application methods, and understanding specific plant-microbe interactions remain. Further research is needed to fine-tune the use of PGPB.

The synergistic effects of PGPR and Rhizobium on nutrient availability, disease resistance, and plant health have been well-documented. PGPRs improve soil structure and nutrient cycling, while Rhizobium plays a crucial role in nitrogen fixation for leguminous crops. The positive impact of PGPR-Rhizobium interactions extends beyond mere yield enhancement, promoting sustainable and environmentally friendly agricultural practices. However, further research is needed to optimize the formulation and application of these beneficial microorganisms for different crops and agroecosystems. Long-term studies are essential to assess the persistence and stability of PGPR-Rhizobium populations in the soil.

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Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Authors' Contribution

Shree Raghavan.R and Ramya Gaddam Krishnakumar: Methodology, Writing – original draft, Writing – review; Editing. Balakumaran Manickam Dakshinamoorthi ; Visualization, Validation, Software, Data Curation. Vidya Prabhakaran ; Writing – review and editing. Nithya Krishnan: Conceptualization, Methodology, Investigation, Data curation, Visualization, Formal analysis, Validation, Writing – original draft, Writing – review and editing.

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