Review Article

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PGPR From Its Discovery to its Commercial Product Development for Sustainable Agriculture: A Review

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Abstract

Plant Growth Promoting Rhizobacteria (PGPR) are a group of beneficial bacteria found in the rhizosphere, the soil surrounding plant roots. These bacteria offer great potential for enhancing plant growth through various mechanisms. It is crucial for PGPR to possess specific characteristics that not only support plant growth but also maintain eco-friendliness. This is particularly important considering the increasing use of chemical inputs in agriculture, which has led to the accumulation of harmful substances in the soil, resulting in reduced fertility over time. Among the various bacterial species within the PGPR group, Pseudomonas fluorescens is one of the well-known and extensively studied. Researchers have conducted studies on the effects of PGPR on plant growth, starting from laboratory experiments and extending to greenhouse trials. These studies have demonstrated the positive impact of PGPR as biofertilizers and biopesticides. The formulation of PGPR strains with specific carriers has been explored to effectively deliver the bacteria to the soil and subsequently to the plants. Such formulations have the potential to reduce the reliance on chemical fertilizers in agricultural practices. Once PGPR formulations are developed, it is available to market and readily available to farmers. This enables the promotion of organic or sustainable farming practices across agricultural areas, reducing the dependence on synthetic chemicals and fostering sustainable agricultural practices.

Keywords: Plant Growth Promoting Rhizobacteria, Biofertilizer, Biopesticides, Nitrogen Fixation, Siderophore, PGPR Formulations

Introduction

Source of macro and micro nutrients for the development of any plant is soil. Both biotic and abiotic factors present in soil plays a crucial role in supplying these nutrients to plant through plant roots. Mixture of salts (macro & micro-nutrients), ions and water are called 'sap' of plant which is being absorbed by plant roots and transported to plant parts through xylem tissue. Under biotic factor most commonly earthworms (Lumbricina) enriches the soil with nutrients through its different methods and microbial help. Soil is the habitat of highest numbers of microorganisms, which are either beneficial or harmful. It has been studied that around 100 years ago farmers recognized microbial support for the growth of plants [1]. Later in the year 1980s Kloepper et al., discovered a special type of bacterial group which found in rhizosphere of plant roots and termed them as Plant Growth Promoting Bactria (PGPR) [2]. These PGPR gets it nutrition for plant in the form of plant exudates in rhizospheric region. After the photosynthesis plants releases around 40% of the whole product in the form of plant exudates from roots which makes rhizosphere rich in nutrients [3]. These PGPR not only gets its essential nutrients from this region but also supports plants growth by making a relation with the plants in which they help plants to uptake the nutrients from the soil and they get food and shelter from the plants to survive to it best by avoiding any type of stress and unfavorable conditions [4, 5]. PGPRs multiple mechanisms enhances the fertility of the soil. Among all the types of bacteria present in rhizoshprere, only about 2–5% of rhizosphere bacteria are PGPR [6]. There are Pseudomonas, Azospirillum, Azobacter, Klebsiella, Enterobacter, Alcaligenes, Burkholderia, Bacillus, and Serratia, which enhance plant growth and yield [7]. This makes a large list of bacteria under each genus.

PGPR performs many different mechanisms which are not only helpful for plant but also to soil health. These mechanisms include fixing of atmospheric nitrogen, increasing the availability of essential nutrients and production of secondary metabolites

[8]. Researcher have done studies on inoculating the rhizobial bacteria in labs and greenhouse which shows the prominent results and have good impact on growth of plant, but on the field scale experiment it showed variable results depending upon the environmental conditions [4]. As these PGPRs helps in plant growth by many methods one of them is nitrogen fixation which increase the soil fertility and this make us to go for organic farming and sustainable farming by not using chemicals like chemical fertilizer in the field which can keep the field productive without damaging the soil and hampering the environment.

PGPR:

- Producing plant hormones
- Enhancing other beneficial bacteria or fungi
- Controlling diseases, nematodes and insect pests

Introduction of PGPR for increasing plant growth promotion in 1950s from the research findings opened new vistas to use PGPR as an alternate to chemical pesticides for the management of soil-borne pathogens [9]. Application of PGPR either as single strain or strain-mixture-based formulations checked pest and disease spread besides increasing growth and yield. Plant treatments with PGPR have been found to increase the root and shoot growth, total plant biomass, and percentage of seed germination, seedling vigor, emergence, plant stand, seed weight, grains, and fodder and fruit yields or reduce the time to flowering [10]. Many PGPR have the property as biocontrol agent some species include Pseudomonas and Bacillus. Inoculation with Pseudomonas fluorescens has shown an increase in root weight 19-43%, number of tillers per plant 10-21%, grain yield 15-43%, and straw yield 22-39% of wheat compared to un-inoculated plants [11]. Moreover, studies have also shown that inoculations with PGPR strain Azotobacter have saved 25-30kgha-1 chemical fertilizer [12].

PGPR's Characteristics

To be classified into PGPR group bacteria need to have plant growth promoting characteristics in addition with other soil health enhancing properties. In the earlier studies it has been found that among all such characteristics PGPR strain should have following characteristics [13]:

- The strain should be highly competent to rhizosphere and should be eco-friendly
- Should promote plant growth by any mechanism
- It should be able to grow and colonize in rhizoshpere in minimum time from small inoculation
- It should be able to perform a broad-spectrum action in the soil
- Every strain/bacterium should be compatible and promoting to other rhizospheric strain/bacteria
- It can tolerate any abiotic stress or physicochemical factors like heat, desiccation, radiations, and oxidants.
- It should be able perform highly efficient than predominating strains of rhizoshpere

PGPR Mechanisms to Promote Plant Growth

Nitrogen Fixation in Leguminous Plants and also Promotes Free Living Nitrogen Fixers

Nitrogen is one of the most important elements in plant synthesis or for growth of plant, as nitrogen is a constituent of biomolecules like nucleic acids (genetic material), peptides, organic acids, and fatty acids which are essential or very important for the structure and functioning of all living beings. In leguminous plants produces a compound called flavonoid compounds, which is being secreted by the roots of the plants. Later rhizobia recognize these compounds which signal for the production of nodulation factors (nod factors) which finally induces the nodulation on the roots. This nodulation helps in fix atmospheric nitrogen in legumes and provides the nitrogen to plants through roots. Nitrogen can be captured and fixed in soils by microorganisms in which one of them is diazotrophic bacteria, which are responsible for the fixation of atmospheric nitrogen into ammonia, this ammonia is the initial substrate for the nitrification process. The nitrification involves the process of transformation of ammonium to nitrate and is carried out by nitrifying bacteria, such as Nitrosomonas spp. or Nitrobacter spp. This process has two main steps. In First step, ammonium ion (NH4 +) is transformed into NH2OH by the action of the enzyme ammonium monooxygenase that catalyzes the oxidation process, requiring two electrons for the reduction of an O2 atom in H2O, and NH2OH is converted to NO2 by the action of the hydroxylamine oxidoreductase enzyme, which is carried out by a group of ammonium-oxidizing bacteria as shown in Figure 1.

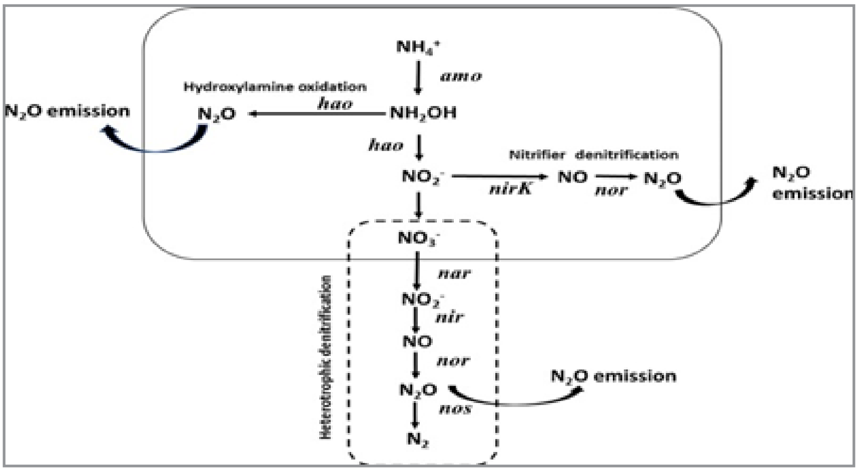

Figure 1: Nitrification and Nitrogen Fixation [14]

The Second step involves the transformation of NO2 into NO3 through the catalysis generated by the enzyme nitrite oxidoreductase secreted by nitrite oxidizing bacteria (NO_2^-), which are chemolithoautotrophs; they are such microorganisms which uses the chemical energy of nitrification to fix CO2 [14]. There are also a group of bacteria collectively called as rhizobia (Rhizobium, Mesorhizobium, and Bradirhizobium) that are capable of associating or forming a symbiotic relationship (highly regulated and specific) with the roots of legume plants.

Promoting Free-Living Nitrogen- Fixing Bacteria and Enhancing other Beneficial Bacteria or Fungi

PGPR enhance plant growth by direct and indirect means, but the specific mechanisms involved have not all been well characterized [7, 9]. Within the plant microbiome or plant environment specific to all plants, plant growth-promoting rhizobacteria (PGPR) can colonize and proliferate/grow within the rhizosphere environment. The rhizosphere is the area immediately surrounding the root in the soil and having the plant root exudates in that area. Root exudates includes many biomolecules in a range of organic acids, amino acids, sugars and other small molecules exuded by the plant roots that act as strong chemo-attractants of the soil microflora/microorganisms. Every plant has its own environment and root exudates which attract specific or a particular microbiota of the soil. On the other hand, soil microbiota also detects the specific chemical in the soil release of plant roots and allows microbiota to efficiently colonize specific rhizosphere and plant roots. A most common and widely known example of specific plant–bacteria communication is that of legume-rhizobia [15]. However, not only does the plant exude compounds that attract a particular microbiome, but there are many mechanisms present in the PGPRs that allow them to detect and recognize specific chemical or root exudates in the soil, acquire nutrients, occupy spaces, and either directly or indirectly inhibit other microbial species, in order to survive and colonize the rhizosphere. After some studies it was found that Pseudomonas spp. is the predominant strain of the rhizobacterial community which laid the foundation to study the importance of rhizosphere colonization. Therefore, it became necessary to study the rhizosphere colonization mechanism for developing any inoculants for plants growth

Increasing Supply of other Nutrients, such as Phosphorus, Sulphur, Iron and Copper

Iron Siderophore

Siderophores are low molecular weight, extracellular compounds which having a high affinity for ferric iron which is secreted by microorganisms in the soil to take up iron from the environment, and their mode of action is to suppression of disease is based on competition for iron with the pathogens. Fluorescent pseudomonas is characterized by the production of yellow-green pigments which is name or termed as pyoverdines which fluoresce under UV light and functions as siderophores. The siderophores which is produced by Fluorescent pseudomonads promotes the plant growth. The siderophores of Fluorescent pseudomonads were later reported to be used in the suppression of plant pathogen's competition for iron between pathogens, and siderophores of Fluorescent pseudomonads have been used in the biocontrol of wilt diseases caused by Fusarium, damping off of cotton caused by Pythium ultimum and Pythium root rot of wheat. Presence of Pyoverdines chelates iron in the rhizosphere and restricts pathogens which require for their growth and pathogenesis. Rhizobacteria produce various types of siderophores (pseudobactin and ferrooxamine B) that chelate the low availability of iron and thus prevent pathogens from acquiring iron.Siderophores are produced by a wide range or large number of bacterial, fungal, and plant species [16]. The siderophores which are produced by PGPR have been various functions in the rhizosphere. Siderophores play a crucial role in the rhizosphere by not only facilitating iron uptake under limited conditions but also inhibiting the growth of potential plant pathogens. Consequently, the production of these compounds is a significant factor in the colonization of the rhizosphere when iron availability is scarce. In Figure 2 it is shown how PGPR simultaneously acts in pathogens and takes Fe ions.

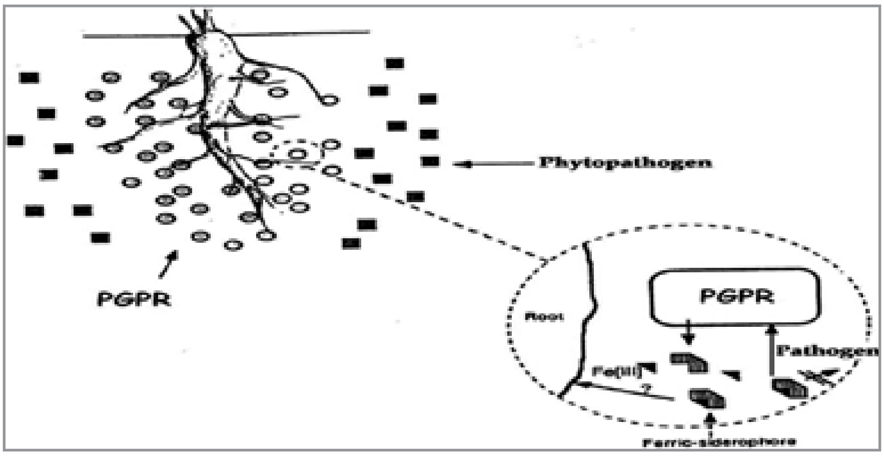

Figure 2: Phytopathogens Suppression by Siderophore-Producing PGPR [17]

Phosphate Solubilization

Phosphorus is one of the most important elements for plants and also for agricultural plant production. It is found in two forms

- organic phosphorus (generally 30% to 50% of the total), which is mostly present in the form of inositol hexaphosphate, or phytate, in which form phosphorus is stored in plants and can be easily degraded by bacteria or fungi
- Inorganic phosphorus, which usually forms insoluble mineral compounds with calcium, aluminum, or manganese.

Most soils contain a large amount of phosphorus. Most of this phosphorus is insoluble and is not available to support plant growth. The amount of soluble phosphorus in most soils is around 1mg/kg of soil, which is insufficient to support plant growth. The distribution of these forms of phosphorus in soils depends on different factors like microbial activity, pH, soil type, and the availability of organic matter. In addition to phytate, which requires enzymatic breakdown before plants can use it; plants obtain phosphorus primarily in the form of orthophosphates and soluble inorganic ions like monobasic ($H2PO4-$) and dibasic ($HPO42-$). Due to its limited availability, both plants and microorganisms compete for phosphorus through precipitation, solubilization, absorption, and desorption processes. Organic phosphorus can be released as a result of soil organic matter mineralization or through specific enzymes that are regulated based on the plant's nutrient requirements [18]. The main mechanism for solubilizing inorganic phosphate involves soil bacteria synthesizing and secreting organic acids, usually derived from glucose oxidation. However, the ability to solubilize phosphate doesn't necessarily correlate with the capacity to colonize the rhizosphere. Phosphate-solubilizing plant growth-promoting rhizobacteria (PGPR) can survive in the rhizosphere by directly taking up phosphorus or by enhancing its bioavailability, which promotes better plant development, including root system growth. It's important to note that mycorrhizal fungi, which beneficially interact with over 90% of vascular plant roots, also play a role in sequestering and solubilizing phosphorus from the soil, providing it to plants.

Producing Plant Hormones

Various strains of plant growth-promoting rhizobacteria (PGPR) produce diverse phytohormones such as cytokinins, indole-3-acetic acid (IAA), and gibberellins, which have been found to influence root structure and promote plant growth [19]. PGPR that produce IAA and gibberellins in the rhizosphere soil play a crucial role in increasing the number of root tips and enhancing root surface area in several herbaceous plants [20]. The application of PGPR-derived cytokinins has been associated with the augmentation of root surface area, root initiation, cell division, and cell enlargement, leading to increased growth of lateral and adventitious roots [21].

Importance and Regulation of Ethylene Level in Plant

Ethylene is a well-known gaseous plant growth regulator that plays a vital role in promoting healthy plant growth. However, when present in excessive amounts, it can have detrimental effects on crop performance by triggering premature leaf senescence and other cellular processes [22]. Beneficial rhizospheric bacteria have the ability to mitigate ethylene accumulation and contribute to the development of robust root structures, which are crucial for plant survival under abiotic stresses. The primary mechanism by which Rhizobium and Pseudomonas rhizobacteria with ACC-deaminase production capability reduce ethylene levels [23]. The application of ACC-deaminase-producing bacteria has shown promising results in decreasing salt-induced ethylene levels, enhancing salt resistance in canola plants, and promoting overall plant growth and crop productivity [24].

Controlling Diseases, Nematodes and Insect Pests

Microorganisms associated with plants engage in ongoing nutritional competition, leading them to develop the synthesis of various antimicrobial compounds as a strategy to compete other microorganisms and establish themselves in specific niches [25]. These antimicrobial compounds are classified based on their effect on microorganisms, with bactericidal agents causing cell death and bacteriostatic agents temporarily inhibiting microbial growth [26]. These compounds exhibit a wide range of chemical diversity, allowing them to target different cellular components and interfere with various microbial processes. For instance, organic acids produced by microorganisms can modify the pH of the surrounding environment, exerting selective pressure on competing microorganisms [27]. Some plants facing infections by phytopathogenic fungi employ the recruitment of microorganisms to combat the infection. As an example, wheat plants inhibited by Gaeumannomyces graminis recruit Pseudomonas spp., which produce the antifungal compound 2,4-diacetylphloroglucinol [28].

Improvement of Plant Resistance Against Abiotic Stresses

Plant growth-promoting bacteria (PGPB) are a diverse group of bacteria that have been extensively studied for their beneficial effects on plant growth and development. They exhibit a wide range of adaptability and can thrive in various environments [29]. Among PGPB, plant growth-promoting rhizobacteria (PGPR) are the most extensively studied. These bacteria colonize the root surface and flourish in the rhizosphere, the soil region influenced by the root system [30]. The term PGPR encompasses bacteria that not only promote visible plant growth but also contribute to increased crop yield by enhancing plant defenses against disease attacks [31]. The acronym PGPR was introduced by Kloepper in 1978 during a study investigating the positive effects of certain rhizobacteria used as seed inoculants to stimulate plant growth. These bacteria, employed as biopesticides, biofertilizers, and phytostimulators, have shown the ability to improve crop yields and provide environmentally friendly crop protection, serving as alternatives to synthetic fertilizers and pesticides. Pseudomonas and Bacillus strains are among the extensively studied PGPR [2] and are recognized for their significant role in disease management due to their effective antibiotic mechanisms [32].

Biopesticidal Activity

Biopesticides play a crucial role in enhancing crop performance under various environmental stresses. One example is the production of calcisol by different plant growth-promoting rhizobacteria (PGPR), which contributes to heat and salt stress resistance. Another approach to mitigate drought stress involves the application of arbuscular mycorrhizal (AM) fungi in conjunction with nitrogen-fixing microorganisms in leguminous plants. This combination can help alleviate the negative impacts of drought. Certain species of Pseudomonas, such as P. putida, have been found to promote sprouting and improve physical growth parameters, such as fresh and dry weight, in cotton plants under high pH and saline conditions. This is achieved by reducing the absorption of $Na+$ ions and enhancing the uptake of calcium, magnesium, and potassium [33].

Development and Production of PGPR formulation

Formulating PGPR products is necessary to ensure convenient application, storage, commercial availability, and field utilization.

Features of an Ideal Formulation

- Enhanced shelf life.
- Non-harmful to crop plants.

- Effective dissolution in water with the ability to release bacteria.
- Tolerance to adverse environmental conditions.
- Cost-effectiveness and reliable control of plant diseases.
- Compatibility with other agrochemicals.
- Availability of low-cost and easily obtainable carriers for formulation development [13].

Carriers

The carriers utilized for PGPR should enable the bacteria to survive for an extended period. These carriers can be of organic or non-organic origin. It is essential that the carriers are economical and easily obtainable.

Organic/Non-Organic Carriers

The organic carriers used for formulation development include peat, turf, talc, lignite, kaolinite, pyrophyllite, zeolite, montmorillonite, alginate, press mud, sawdust and vermiculite. Carriers increase the survival rate of bacteria by protecting it from desiccation and death of cells [34]. The shelf life of bacteria varies, depending upon bacterial genera, carriers and their particle size. Survival of P. fluorescens (2-79RN10, W4F393) in montmorillonite, zeolite and vermiculite with smaller particle size increased the survival rate than in kaolinite, pyrophyllite and talc with bigger particle size. The carriers with smaller particle size have increased surface area, which increases resistance to desiccation of bacteria by the increased coverage of bacterial cells [35].

Formulations

Liquid fermentation technology was employed to develop formulations of fluorescent pseudomonads. These formulations involved mixing the biomass obtained from the fermentor with various carrier materials and stickers [36]. For instance, a talc-based formulation of Pseudomonas fluorescens was created for managing rice blast caused by Pyricularia grisea. Methyl cellulose and talc were blended in ratio of 1:4 and combined with an equal volume of bacterial suspension at a concentration of 10 cfu/ml [37]. Another talc-based strain mixture formulation of fluorescent pseudomonads was developed by combining equal volumes of individual strains with talc [38]. These talc-based strain mixtures demonstrated efficacy against rice sheath blight and increased plant yield in field conditions compared to the application of individual strains. Talc- and peat-based formulations of Pseudomonas chlororaphis and Bacillus subtilis were also prepared for managing turmeric rhizome rot [39].

There are differing opinions regarding the use of carboxymethyl cellulose (CMC) as a sticker in the formulations. Some argue for a 1:4 ratio of CMC to talc, while others suggest ratio of 1:100. The feasibility of the technique and the shelf life of the product need to be evaluated to ensure the viability of the technology in disease management and promote organic farming. It is important to consider the production cost implications to ensure grower adoption of the technology.

Talc Formulation

Talc, also known as steatite or soapstone, is a natural mineral composed of various minerals combined with chloride and carbonate. Its chemical composition is magnesium silicate [$Mg_3Si_4O_3(OH)_2$]. Talc is commercially available in powder form and finds wide applications in various industries. It possesses characteristics such as low moisture equilibrium, relative hydrophobicity, chemical inertness, and reduced moisture absorption. These properties make talc an ideal choice for preventing the formation of hydrate bridges and enabling longer storage periods [36]. Due to its inert nature and easy availability from soapstone industries, talc is commonly used as a carrier for formulation development. Studies have shown the potential of talc as a carrier for formulating rhizobacteria [40]. For instance, when fluorescent pseudomonads were mixed with 20% xanthan gum in talc, their viability remained unaffected after two months of storage at 4 °C. This demonstrates the suitability of talc as a carrier for maintaining the efficacy of microorganisms during storage [36].

Peat Formulation

Peat, also known as turf, is a carbonized vegetable tissue that forms in wet conditions through the decomposition of various plants and mosses. It is created by the gradual decay of layers of aquatic and semi-aquatic plants such as sedges, reeds, rushes, and mosses. Peat soils are commonly used as carrier materials for formulating plant growth-promoting bacteria (PGPR). However, peat carriers have certain drawbacks. They can harbor a high level of contaminants, and the quality of peat can vary, making it less readily available worldwide. Additionally, sterilizing peat through heat treatment can release toxic substances that can negatively affect bacterial viability [30].

Despite these challenges, peat-based formulations have shown promising shelf lives for certain PGPR. For example, a formulation of Azospirillum brasilense using peat as the carrier demonstrated a shelf life of up to 4 months, with a population load of 107 colony-forming units (cfu) per gram of the product. This population was found to be sufficient for successful plant inoculation [30]. In the case of Pseudomonas fluorescens, its shelf life in a peat-based formulation was maintained for up to 8 months, with a population of 2.8 × 106 cfu per gram of the product [36]. Similarly, the shelf life of P. chlororaphis (PA23) and Bacillus subtilis (CBE4) in peat carriers was retained for more than six months in separate studies [39].

Press Mud Formulation

Press mud, a by-product of the sugar industry, can be effectively utilized as a carrier material for Azospirillum spp. This alternative carrier has been found to enhance the survival of Azospirillum spp. compared to lignite, which is commonly used as a carrier material in India [41]. Through the process of vermi-composting, press mud undergoes decomposition with the assistance of earthworms, resulting in a suitable medium for incorporating Azospirillum spp. By utilizing press mud as a carrier, the viability and efficacy of Azospirillum spp. can be maximized, offering a sustainable and cost-effective approach for agricultural applications.

Vermiculite Formulation

Vermiculite, a mineral with a mica-like structure, is commonly used to enhance aeration and moisture retention in various applications, including potting mixtures. It is also utilized as a carrier material for the development of microbial formulations. A formulation of Pseudomonas fluorescens (strain Pf1) based on vermiculite demonstrated a shelf life of 8 months, with a viable bacterial count of 1 × 106 cfu/g [36]. Similarly, vermiculite-based formulations of Azospirillum retained their shelf life for up to 10 months, with a viable cell count of 1.3 × 107 cfu/g after 44 weeks of storage [42]. Vermiculite serves as an effective carrier material for these microbial agents, providing long-term viability and ensuring their efficacy for agricultural applications.

Microencapsulation

Microcapsules containing rhizobacteria are composed of a polymer coating that encapsulates a liquid phase containing dispersed bacteria. These microcapsules are characterized by their size distribution, morphology, and bacterial content. The process of microencapsulation involves mixing a gelatin polyphosphate polymer pair (81:19 w/w) at an acidic pH with rhizobacteria suspended in it [43]. However, the shelf life of microencapsulated rhizobacteria tends to decline rapidly due to the barrier effect of the polymers, which restricts oxygen availability. To overcome this limitation, researchers have developed microcapsules using spray drying techniques. The release of Pseudomonas fluorescens and Pseudomonas putida from these microencapsulated pellets was observed after 15 minutes of immersion in an aqueous buffer, indicating that water serves as a trigger for bacterial release. Although microencapsulation facilitates bacterial formulation, further refinement of the technology is necessary to ensure the early release of bacterial cells and their effective establishment in the infection sites to counteract pathogen establishment. Most experiments on microencapsulation have been limited to laboratory settings, and the technology needs to be standardized for industrial application in order to assess its technical feasibility and promote its widespread use in the field.

Global Biofertilizer Market

Over the past few decades, there has been a significant increase in the production and utilization of biofertilizers worldwide. This growth can be attributed to the limited availability of cultivable land and the growing demand for agricultural products to feed the increasing global population. Despite the rapid expansion, the biofertilizer market still represents a small fraction of the synthetic agrochemicals market [44].

Within the biofertilizer market, nitrogen-fixing biofertilizers hold the largest market share, accounting for approximately 80% of the market. Following closely behind are phosphate-solubilizing biofertilizers, which make up a smaller portion with around 14% of the market. Some of the major nitrogen-fixing biofertilizers available in the market include Rhizobium spp., Azotobacter spp., and Azospirillum spp. These biofertilizers are primarily used for cultivating pulses, leguminous crops, and selected cereals and cash crops.

The global biofertilizer market encompasses various regions around the world, including North America, Europe, Asia-Pacific, Latin America, the Middle East, and Africa. In terms of revenue generated from biofertilizer production, North America (USA, Canada, and Mexico) holds the dominant position in the global market, followed by Europe (Germany, UK, Spain, Italy, Hungary, and France), and the Asia-Pacific region (China, Japan, India, Australia, New Zealand, and other Asian countries). As of 2017, the biofertilizer markets were valued at USD 495 million in North America, USD 450 million in Europe, USD 284 million in Asia-Pacific, USD 240 million in South America, and USD 44 million in Africa. It is projected that the global biofertilizer market will reach a value of USD 3.5 billion by 2025 [45].

Future Aspects

In the current scenario the world's demand for food and grains is getting high day by day as the high rise in the population and to fulfill the demand of the world, farmers are forced to use the chemicals in the agriculture practices cause chemical fertilizers and pesticides are not only cheap but also easily available in market cause the marketing of such products is high due to great support, low manufacturing cost, great number of manufacturing companies and competition between then promotes them to go for low cost selling and making their product available everywhere easily. Plant Growth Promoting Rhizobacteria (PGPR) is the new ear's new revolution in the field of agriculture as we discussed in the above review paper on PGPR, that how the PGPR is useful in promoting the plant growth and its yield.

PGPRs are the microorganisms as they are bacteria they are present all around and their growth do not need any extra work other than providing them the optimal condition and environment. PGPR has a great impact in the world in upcoming scenario, use of chemical in the agricultural field slowly degrading the fertile land to unfertile one due to accumulation of chemicals on the land. PGPR are not widely known on grass root level so far but slowly it is gaining the attention of farmers as we are now looking to move toward the sustainable cum organic farming, as people are now thinking about the good health and avoiding the unhealthy and chemical used food and this promoting the use of organic materials in the agriculture and avoiding the use of chemicals. Formulations of PGPRs are also not very expensive process as for the production of different strains of bacteria in different carriers. Proper downstream processing of the PGPR formulation can lead to avoid the entire chemicals in the agriculture and we can promote the sustainable development.

Conclusion

The agricultural industry plays a critical role in meeting the increasing global demand for food, as the world population continues to grow. To ensure high crop yields with minimal investment, it is necessary to develop processes and methods that optimize productivity. While the Green Revolution brought significant advancements in crop productivity, it also resulted in environmental concerns. The use of chemical fertilizers has proven detrimental to soil and environmental health. In contrast, biofertilizers are natural products that do not pose threats to the ecosystem. Therefore, incorporating natural-products-based fertilizers is essential for managing long-term soil fertility and sustaining crop productivity in a manner that aligns with the principles of sustainable agriculture.

Over the past decade, there has been a notable shift towards the increased use of biological inoculants instead of agrochemicals worldwide. This shift represents a revolution in sustainable agriculture. The interactions among bioinoculant microorganisms, resident soil microorganisms, and host plants form a vital triad. These interactions not only promote the overall growth and higher productivity of crop plants but also contribute to maintaining the health of our planet and proper biogeochemical cycling.

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