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Biofertilizer and Consortium Development: An Updated Review

YUVARANI MUTHUSAMY[1], KAVITHA SENGODAN[2], MALARVIZHI ARTHANARI[1], RAMESH KANDHASAMY[2] and KUPPANNAN GOBIANAND[1]*

[1]Department of Microbiology, Vivekanandha College of Arts and Sciences for Women (Autonomous), Elayampalayam, Namakkal (DT), Tamilnadu, India.
[2]Department of Microbiology, Kongu College of Arts and Science, Vennaimalai (PO), Karur, Tamilnadu, India.

Abstract

To boost crop yield on arable land, fertilizers have been extensively utilized. A country may become food-self-sufficient by using more chemical fertilizers in agriculture, yet chemicals are harmful to the environment and living things. Biofertilizers are organic substances that make use of microorganisms to increase the fertility of soil, which helps safeguard the soil's health and also the quality of crop products. Biofertilizers provide nutrients through natural processes like nitrogen fixation, phosphorus solubilization, and plant growth-inducing chemical synthesis. There are some important microorganisms that are used in biofertilizer production: *Azotobacter, Azospirillum*, *Phosphobacter*, and *Rhizobacter.* There is a significant growth result when the biofertilizers are inoculated with two or three microorganisms rather than a single one, i.e., a consortium. On co-inoculation of the microorganisms show to stimulate plant growth, nodulation and nitrogen fixation. Other microorganisms, like *Pseudomonas* and *Bacillus*, act as an effective biocontrol system. Some microorganisms are able to survive in a vast range of environments, expecting synergistic modes of action. They are also environment-friendly and responsible for the continuous availability of nutrients from natural sources. This review describes the importance of biofertilizers, widely used strains, and their potential significance in crop production.

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Introduction

Despite having a short history in contemporary agriculture, chemical pesticides and fertilizers have significantly increased agricultural production during the past 50 years. Environmentally sustainable plant preservation has received less attention due

CONTACT Kuppannan Gobianand ✉ rajgobi@gmail.com Department of Microbiology, Vivekanandha College of Arts and Sciences for Women (Autonomous), Elayampalayam, Namakkal (DT), Tamilnadu, India.

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to its toxicity toward humans, animals, plants, and the environment. Additionally, there is still no solution to the issue of insect resistance to widely used insecticides. Because of conventional agriculture, which is essential for supplying the world's expanding population with food, there has been an increase in the usage of chemical fertilizers and pesticides.[1]

By 2030, the FAO predicts that demand for agricultural products will grow by 60%. One of the biggest difficulties in the 21st century is increasing output while maintaining environmental safety. To boost crop production on arable land, fertilizers have been extensively used. A country may become food-self-sufficient by using more chemical fertilizers in agriculture, yet chemicals are harmful to the environment and living things. Additionally, chemical fertilizers are costly, have an adverse effect on the soil's fertility and ability to retain water, create nutritional imbalances, and contribute to intolerable levels of water contamination. Contrarily, biofertilizers are inexpensive, practical, non-toxic, and simple to use; they support preserving the agricultural land's biodiversity and soil structure. As a result, they are a good alternative to chemical fertilizers.[2,3]

According to Mishra *et al.* (2013),[4] biofertilizer is a mixture of live or latent cells that promote nitrogen fixing, phosphate solubilizing, or cellulolytic microorganisms that are applied to soil, seeds, roots, or composting areas in order to increase the quantity of these mutualistic beneficial microorganisms and speed up those microbial processes that increase the availability of nutrients that are then more readily assimilated. According to Malusá and Vassilev's theory (2014),[5] a biofertilizer is a substance that has been particularly prepared to include one or more microorganisms that enhance nutritional status (plant growth and yield) by either substituting soil nutrients, enhancing plant access to nutrients, or making nutrients more available to plants.

The market for biofertilizers is divided into different categories based on the microorganisms used, including *Rhizobium*, *Azotobacter, Azospirillum*, blue-green algae, phosphate-solubilizing bacteria, Mycorrhiza, and other microorganisms; the technology used, including carrier-enriched biofertilizers, liquid biofertilizers, and other technology types; and the application, such as seed treatment and soil treatment.[6]

Nutrient-delivery devices with biological components are known as biofertilizers. The biofertilizer's nitrogen fixer and phosphate solubilizer fix 20–40 kg of nitrogen per acre. By employing biofertilizer to secure production, the cost of soil fertility is maintained, and continual application of biofertilizer makes the soil extremely fertile for a good yield. The biofertilizer can be prepared as a liquid to spray on plants or as a soil additive. In order to meet the rising demand for food that is safe and residue-free, modern agriculture needs to use biopesticides and biofertilizers.[7]

Arbuscular mycorrhizal fungi (AMF), also referred to as plant growth-promoting rhizobacteria, are among the beneficial bacteria and fungi that make up the soil's natural microflora and are crucial to organic farming (PGPR). By fixing nitrogen, releasing substances that influence plant growth, solubilizing or mineralizing phosphate and potassium, creating antibiotics, and decomposing organic materials in the soil The environment of the soil is kept rich in a range of micro- and macronutrients by biofertilizers. Numerous bacteria, such as Pseudomonas, *Azospirillum*, *Azotobacter, Klebsiella*, *Enterobacter*, *Alcaligenes*, *Arthrobacter*, *Burkholderia*, *Bacillus*, and *Serratia*, have been demonstrated to promote plant growth either directly by assisting in the acquisition of resources (nitrogen, phosphorus, and essential minerals) or indirectly by reducing the inhibitory effects of various pathogens in the soil.[8]

Auxins, gibberellins, cytokinins, abscisic acid, and ethylene are the five most well-known phytohormone families, collectively known as the "classical five." Some PGPR is known to produce IAA, gibberellic acid, and cytokinins in the rhizosphere soil, and as a result, they play an essential role in increasing the root surface area and the number of root tips in different types of plants. The coordination of a variety of physiological processes in plants, such as quiescence, seed germination, root development, fluorescence, branching, tillering, and fruit ripening, is aided by plant hormones. By stimulating or inhibiting gene expression as well as the production of enzymes, pigments, and metabolites, they increase plants' resistance to environmental stresses. Biofertilizers multiply when applied as soil or seed inoculants, take part in the nutrient cycle, and raise crop productivity. Typically, 60 to 90 percent of the fertilizer used is lost, with plants utilizing only 10 to 40 percent. In this regard, microbial inoculants are necessary for integrated nutrient management systems to sustain agricultural production and a healthy environment.[9]

One-third of the global gross domestic product (GDP) is generated by the agriculture sector. However, the world's population is anticipated to reach 9.5 billion by 2050 due to the trend toward an increased human population, which leads to an increase in the demand for food. Chemical fertilizers are persistent pollutants in nature because they contain radionuclides and heavy metals that are hard to break down. Another significant problem related to the overuse of chemical fertilizers is the eutrophication of water sources. To solve these pollution issues posing risks to the public's health, ecologically sustainable alternatives that could reduce the usage of chemical fertilizers must be developed.[10,11]

Products called biofertilizers include living cells from diverse microorganisms that can use biological processes to change nutritionally important components from an unavailable to an available state. in order to satisfy the demands of plant biologists and agriculturists, whose work focuses on creating wholesome, practical techniques for enhancing soil quality by nourishing and maintaining the advantageous and indigenous flora of microorganisms. The objective of this review is to investigate the function of biofertilizers in sustainable agriculture. The benefits of using biofertilizers are also underlined in terms of better nutritional profiles, plant growth and productivity, and stress tolerance. Additionally, it emphasizes current research in the area of agricultural management.[12]

Disadvantages of Synthetic Fertilizer

Fertilizers should be used carefully since they pollute the soil, contaminate water basins, kill beneficial insects and microorganisms, increase the risk of illness in crops, and decrease soil fertility. Demand exceeds supply by a wide margin. By 2020, 28.8 million metric tons of nutrients will be required to produce the anticipated 321 million metric tons of food grain, but only 21.6 million metric tons of those nutrients will be accessible, leaving a deficit of almost 7.2 million metric tons. Due to a rising supply-demand mismatch, small and marginal farmers are finding it harder and harder to pay this, which puts sustainable agriculture at risk by reducing soil fertility.[13]

Fossil fuels are out, and fertilizer prices are rising as a result of the energy crisis. Due to a rising supply-demand mismatch, small and marginal farmers are finding it harder and harder to pay this, which puts sustainable agriculture at risk by reducing soil fertility. In addition to the previously mentioned facts, long-term usage of biofertilizers is more affordable, environmentally benign, productive, and available to marginal and small farmers than chemical fertilizers. However, if phosphorus is added to chemical fertilizer in a soluble form, most of it quickly dissipates in the soil and disappears, which negatively impacts the growth of healthy plants. Moreover, because insoluble phosphorus is present in various types of organic forms, including inositol phosphate (soil phytate), phosphomonoesters, and phosphodiesters, plants cannot metabolize it.[14]

Modern agriculture makes extensive use of pesticides, chemical fertilizers, constant irrigation, improved seeds, and herbicides. Although their usage in agriculture increases output, it is concerning that their wasteful use has a detrimental impact on the environment's quality and soil productivity. Plants are grown in soils that are rich in nitrogen. Vegetables like lettuce and spinach leaves include nitrosamines, which are known to cause cancer. NO_3 and NO_2 have accumulated unhealthily. Additional problems caused by excessive synthetic fertilizer include nutrient loss, groundwater and surface water contamination, soil acidification or basification, loss of beneficial microbial populations, and increased sensitivity to dangerous insects. The eutrophication of water sources is another major problem due to the overuse of chemical fertilizers.[15]

Additionally, a single mineral fertilizer speeds up the decomposition of soil organic matter, impairing soil structure, decreasing soil aggregation, and causing nutrient loss by leaching, fixation, and greenhouse gas emissions. The ability of soil to maintain optimum crop development and output may be influenced by the long-term use of chemical fertilizers. As a result, we cannot always depend on chemical fertilizers to produce crops. When chemical fertilizers are applied, acids like sulfuric acid and hydrochloric acid build up and promote soil friability, which is bad for the soil. Because soil particles are dispersed by chemical fertilizers, the soil becomes compacted and has poor air and drainage permeability.[16]

Nitrogen fixers (N-fixers), potassium solubilizers (K-solubilizers), phosphorus solubilizers (P-solubilizers), and rhizobacteria that promote plant growth are the most widely used biofertilizers (PGPR). Cyanobacteria can be used as biofertilizers, which is advantageous for farmers who are financially unstable and cannot afford to purchase costlier chemical fertilizers.

Biofertilizers accelerate flowering and increase seedling survival. The fact that parental inocula are sufficient for development and multiplication after utilizing biofertilizers constantly for three to four years is another advantage. There are various benefits to organic manure's balanced supply of macro- and micronutrients. An increase in soil microbial activity can enhance the physical, chemical, and nutritional characteristics of the soil. Chemical fertilizers tend to be more expensive and difficult to find than organic fertilizers. Organic matter is the foundation of soil fertility. Microbial fertilizers play a significant role in plant nutrition and are cost-effective, non-bulky, and environmentally benign.[17]

Bio-fertilizers increase soil fertility, require less energy, reduce soil and water contamination, increase productivity per area, support phytopathogenic organism antagonism, and support biological control. Biofertilizers have several benefits from an economic, social, and environmental perspective. The mobility and availability of minerals necessary for plant growth are impacted by microbial activity in agriculture, which reduces the need for chemical fertilizers. The distribution of plant nutrients is known to promote plant development, and bio-fertilizers that contain beneficial microorganisms rather than artificial chemicals may support soil production and environmental sustainability.[18]

Bacterial Strains are Commonly used in Biofertilizers.

Based on their purposes and modes of operation, biofertilizers are divided into many categories. Nitrogen fixers (N-fixers), potassium solubilizers (K-solubilizers), phosphorus solubilizers (P-solubilizers), and rhizobacteria that promote plant growth are the most widely used biofertilizers (PGPR). The potential role of bacteria as biofertilizers in the growth and development of plants is depicted in Figure 1. Nitrogen is the nutrient that limits plant development the most. Chemicals released into the soil by plant roots enable the colonization of bacteria in the plant rhizosphere and the fixation of nitrogen. They can, to varying degrees, successfully take the place of chemical fertilizers, reducing the chemical load on the environment. *Azotobacter* and *Azospirillum*, as well as symbionts like *Rhizobium*, *Frankia*, and Azolla, are free-living microorganisms. *Rhizobium*, Meso*rhizobium*, Azo*rhizobium*, Brady*rhizobium*, Sino*rhizobium*, and Allo*rhizobium* are N2-fixing bacteria associated with legumes; those with non-legumes include Achromobacter, *Alcaligenes*, *Arthrobacter*, Acetobacter, *Azomonas*, *Beijerinckia*, *Clostridium*, *Bacillus*, *Enterobacter*, *Erwinia*, and *Desulfovi*. Although several genera have been isolated from the rhizosphere, members of the genera *Azospirillum* and *Azotobacter,* in particular, have been extensively studied to boost the production of cereals and legumes in the field.[18,19]

One of the best examples of symbiotic nitrogen fixation is the *Rhizobium* bacterium, which belongs to the Rhizobiaceae family. The bacteria affect the legumes' roots and produce nodules where they convert nitrogen-containing molecules to ammonia, which the plant utilizes to produce proteins, vitamins, and other nitrogen-containing compounds. These root nodules consequently function as ammonia manufacturing plants.[20] According to Sara *et al.* (2013),[21] *Rhizobium* treatment boosted plant height, seed germination, leaf chlorophyll, and N content, which all contributed to an increase in crop growth. *Rhizobium*, *Bradyshzodium*, Sino*rhizobium*, Azo*rhizobium*, and Meso*rhizobium* are all members of the genus *Rhizobia*. Symbiosis accounts for around 80% of the nitrogen that is fixed biologically. *Rhizobium* can thus replace chemical N fertilizers and is commonly used in agronomic techniques to ensure proper nitrogen levels.[22]

Azotobacter contributes significantly to the nitrogen cycle in nature because of its extensive metabolic capabilities. *Azotobacter* has the capacity to produce and secrete large quantities of biologically active substances, including gibberellins, nicotinic acid, pantothenic acid, biotin, heterodoxies, and vitamins like thiamine and riboflavin. It can also secrete ammonia in the rhizosphere in the presence of gibberellins. In addition to this, its function in nitrogen fixation prevents the growth of certain harmful fungi in the environment.[23,24] *Azotobacter*s can be found in neutral or alkaline soils, and A. *chroococcum* is the most common species in arable land. *A. lipoferum* and A. brasilense have been proven to have the largest global distribution and vaccine benefits among the species of the genus *Azospirillum*, which also includes *A. amazonense, A. halopraeferens,* and *A. brasilense*. *Azospirillum* forms associative symbioses with many plants, notably those that have the C4-dicarboxylic pathway of photosynthesis since they grow and fix nitrogen on salts of organic acids like malic and aspartic acid (Hatch and Slack pathway). As a result, it is mostly advised for crops including maize, sugarcane, sorghum, and pearl millet. *Azospirillum* fixes atmospheric nitrogen, which generates compounds that encourage plant growth, such as Indole Acetic Acid (IAA) and Indole Butyric Acid (IBA), and speeds up the rate at which plant roots absorb minerals, all of which boost plant production. Somers *et al.* have shown that A. brasilense can synthesize phenylacetic acid (PAA), an auxin-like molecule with an anti-microbial effect. Rice and sugarcane have varieties of Herba spirillum in their roots, stems, and leaves. They stimulate root growth and nutrient intake while synthesizing growth promoters (IAA, gibberellin, and cytokinins; N, P, and K).[25]

Acetobacter diazotrophicus, another diazotroph, is a nitrogen fixer found in the roots, stems, and leaves of sugarcane and sugar beet crops and is administered by soil treatment. Additionally, it makes growth stimulants like IAA, which aid in the intake of nutrients, seed germination, and root development.[26]

A broad group of prokaryotes known as cyanobacteria, sometimes known as blue-green algae, includes *Nostoc*, *Anabaena*, *Oscillatoria*, *Aulosira*, and *Lyngbya.*[27] They make a substantial contribution to the availability of the vitamin B complex and substances that promote plant growth, such as auxins, indole acetic acid, and gibberellic acid. Because they are so widespread in paddy, they also fix 20–30 kg of nitrogen per hectare in submerged rice fields, which is the reason they are often referred to as "paddy organisms." Cyanobacteria have been reported to enhance seed germination, shoot and root growth, and wheat and rice yields. *Azolla* is used as a biofertilizer for rice crops because of its quick disintegration in the soil and efficient nitrogen supply to rice plants. In addition to fixing nitrogen, these biofertilizers or biomanures also supply sizeable amounts of P, K, S, Zn, Fe, Mb, and other micronutrients. Due to their high biomass output, *Azolla caroliniana*, *Azolla microphylla*, *Azolla filiculoides*, and *Azolla mexicana* have recently been introduced to India. Azolla is used as a biofertilizer in many countries, including Vietnam, China, Thailand, and the Philippines. Utilizing this biofertilizer's tolerance for metal is another benefit. It can therefore be utilized in areas where there is a lot of metal pollution.[28]

About 0.2% of the dry weight of plants is composed of phosphorus, a crucial nutrient for plant growth and development. Phosphorus is now the least movable macronutrient among those available to plants in most soil types. To change phosphate from its insoluble forms to its soluble forms, microorganisms are required. The PSB can release metabolites such as organic acids with hydroxyl (gluconic) and carboxyl (ketogluconic) groups that chelate the cation connected to the phosphate and convert it into the soluble form that plants can use. In addition, the generated acids reduce the pH of the soil and dissolve the bound phosphate, making it available to the plants. Potassium (K) is the second most common and important nutrient for plants, behind nitrogen and phosphorus. It has been demonstrated that a range of bacterial and fungal strains may convert the insoluble K into soluble forms via a number of different techniques, such as the production of acids, chelation, acidolysis, complexolysis, and exchange processes. Two different classes of biofertilizers that can dissolve potassium are *Bacillus* spp. and *Aspergillus niger.*[29,30]

Sulfur is another essential element for plants. An example of a bacterium that can oxidize sulfur is *Thiobacillus* spp. *T. thioxidans* and *T. thioparous* can create sulfates that are useful to plants and help with plant nutrition by oxidizing sulfur. Inoculating Thio*bacillus* with elemental sulphur promotes the latter's oxidation, which increases the availability of nutrients in the soil and, as a result, the growth of plants, according to a recent study.[31,32]

In very small quantities (5-100 mg/kg), zinc, one of the essential minerals, is required by tissues for plant growth and reproduction. *Mycorrhiza, Saccharomyces* species, and different genera of rhizobacteria, including *Pseudomonas* species and *Bacillus* species, are believed to improve the availability of Zn in soil. These microorganisms solubilize zinc via oxidoreductive systems and chelated ligands. These bacteria also produce phytochromes, antibiotics, vitamins, and antifungal substances that have a variety of positive effects on the plant.[33,34,35]

A type of bacteria known as plant growth-promoting rhizobacteria (PGPR) is found in the rhizosphere. A few PGPRs can dissolve phosphate.[36] As a result, there are more phosphate ions available in the soil for the plants to quickly assimilate. When isolated from rhizospheric soil, *Kocuria turfanensis* strain 2M4 was discovered to produce siderophore, IAA, and phosphate.[37] Compared to the untreated control, vegetable crops like cucumber, tomato, and squash exhibited higher growth factors after being treated with *Anabaena vaginicola* and *Nostoc calcicola*. These growth-related variables included plant height, fresh and dry root weight, and root length. It was also demonstrated that this treatment made auxins like IBA, which play a role in plant root development, available in the range of 1.275–2.958 g/g dry weight with traces of IAA in microalgal cells.[38,39]

Table 1: Bacterial strains used in biofertilizer

S.NO	STRAINS	METABOLITES
1	*Azotobacter*	Thiamine, riboflavin, nicotinic acid, pantothenic acid, biotic acid, gibberllin
2	*Azospirillum*	Indole acetic acid (IAA), Indole butyric acid (IBA)
3	*Herba spirillum*	IAA,gibberllin,cytokinin
4	*Cyanobacteria*	Auxin,IAA,gibberellic acid
5	Phosphate soplubilizing bacteria	Organic acids (hydroxyl and carboxyl groups)
6	*Rhizobacteria*	Phytochromes,antibiotics,vitamins,antifungal substances

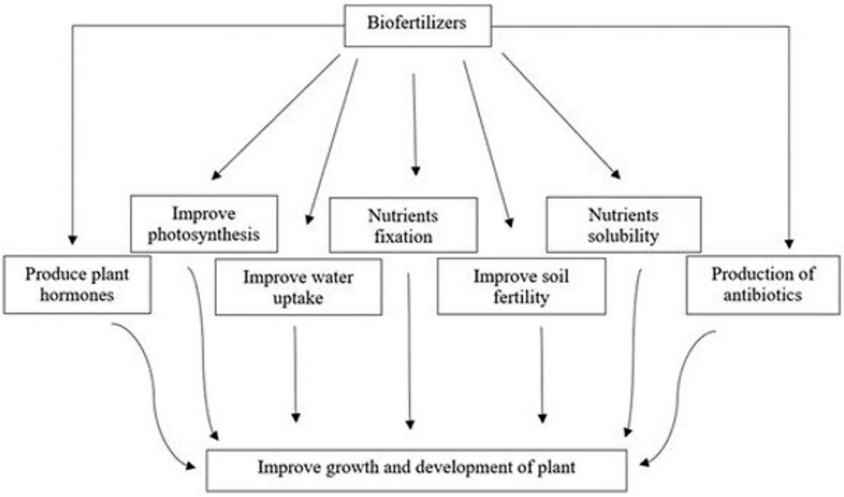

Fig. 1: Advantages of biofertilisers

Mechanism of Action

Effective phosphate solubilizers have been identified as ectorhizospheric strains of pseudomonads, bacilli, and endosymbiotic bacteria from rhizobia. The primary process for bacterial solubilization of mineral phosphates is thought to be the formation of organic acids. Two genes that are involved in the manufacture of gluconic acid have been cloned: PQQ synthase and gabY. *Pseudomonas* sp., *Erwinia herbicola*, *Pseudomonas cepacia*, and *Burkholderia* cepacia all create gluconic acid, which is the main organic acid they manufacture. Significant amounts of 2-ketogluconic acid are produced by *Bacillus* firmus, *Rhizobium* meliloti, and *Rhizobium leguminosarum*. Different phosphate-solubilizing bacteria also produce other organic acids, including lactic, isovaleric, isobutyric, acetic, glycolic, oxalic, malonic, and succinic acids.[40,41,42]

Through a variety of processes, PGPR plays an important role in promoting plant growth. Abiotic stress tolerance in plants, fixing nutrients for simple absorption, plant growth regulators, the production of siderophores and volatile organic compounds, and protection enzymes like chitinase, glucanase, and ACC-deaminase for the prevention of plant diseases are just a few of the ways that PGPR promotes plant growth. However, depending on the host plant type, distinct PGPRs have varied modes of action.[43,44,45]

For instance, nitrogen, which is important for the synthesis of proteins and amino acids, is the nutrient that limits plant growth the most. Prokaryotes are the only organisms that have the machinery for converting atmospheric nitrogen into organic forms that plants can utilize. In temperate climates, cereals are usually found alongside a rare type of nitrogen-fixing organism called *Azospirillum*. It has also been claimed that *Azospirillum* can boost rice crop yields. Phosphate can be solubilized by certain PGPRs. As a result, there are more phosphate ions available in the soil for the plants to readily assimilate. *Kocuria turfanensis* strain 2M4 was found to generate siderophore, IAA, and phosphate when it was isolated from rhizospheric soil. Rice's ability to absorb nutrients was examined by Lavakush *et al.* (2014).[46] *Pseudomonas fluorescens*, *Pseudomonas putida,* and *Pseudomonas fluorescens* were some of the PGPR strains that were employed.[46,47]

Phytostimulator, also known as a "plant growth regulator," is one of the names for the primary mechanisms of action used by PGPR to promote growth. Microorganisms that have the capacity to create or modify the concentration of growth regulators like IAA, GA, cytokinins, and ethylene are referred to as this. The creation of phytohormones (plant hormones) such as auxins, cytokinins, and GA is the process that is being proposed. Phytohormones are organic compounds that are present in plants in very small amounts and have an impact on their biochemical, physiological, and morphological processes. The synthesis of phytohormones is tightly controlled. Plant growth regulators are phytohormones that are produced exogenously by both natural and artificial processes rather than by the plants themselves. The following are some examples of phytohormones that function as plant growth regulators and are either directly or indirectly produced by PGPR.[49]

As further evidenced by Ahmed and Hasnain's 2010 discovery that auxin-producing *Bacillus* spp. has a favorable impact on promoting the growth of *Solanum tuberosum*, auxin is one of the essential chemicals that control most plant activities directly or indirectly. Indole-3-acetic acid (IAA) is one of the most potent and well-known auxins in plants (Hayat, 2010). According to Spaepen and Vacheron, exogenous IAA regulates a variety of processes in plant development and growth. Low levels of IAA can promote primary root elongation, whereas high levels of IAA reduce primary root length, promote the formation of root hairs, and promote the growth of secondary roots. The increased root surface area and length caused by bacterial IAA allow plants to acquire soil nutrients more easily. One of the phytohormones, gibberellin (GA), is essential for the growth of stems and leaves as well as for the germination and emergence of seeds. Shoot elongation, however, is the physiological consequence of GA that is most noticeable. According to research by Khan *et al.*, (2014), tomato plants injected with *Sphingomonas* sp.[49,50,51]

The growth properties of the LK11 strain have increased significantly. Cytokinins induce vascular differentiation, vascular cambium sensitivity, and cell division in plants. However, main root elongation and lateral root formation are inhibited.[52,53] The oriental Thuja seedlings infected with cytokinin-producing *Bacillus* subtilis strains, according to Liu F *et al.*, (2013),[54] were more tolerant to stress brought on by drought. Another hormone found in plants is ethylene, which is known to control a variety of activities, including fruit ripening, leaf abscission, and fruit ripening (Figure 1). Furthermore, ethylene causes defoliation and cellular processes that limit root and stem growth as well as early senescence at high doses, all of which have a negative impact on crop production. In reaction to exposure to many types of environmental stress, such as cold, drought, flooding, infections with pathogens, and the presence of heavy metals, the plants produce 1-aminocyclopropane-1-carboxylate (ACC), which is the precursor for ethylene. Under stressful circumstances, high quantities of ethylene can block some activities, like root elongation or nitrogen fixation in legumes, and induce senescence.[55,56]

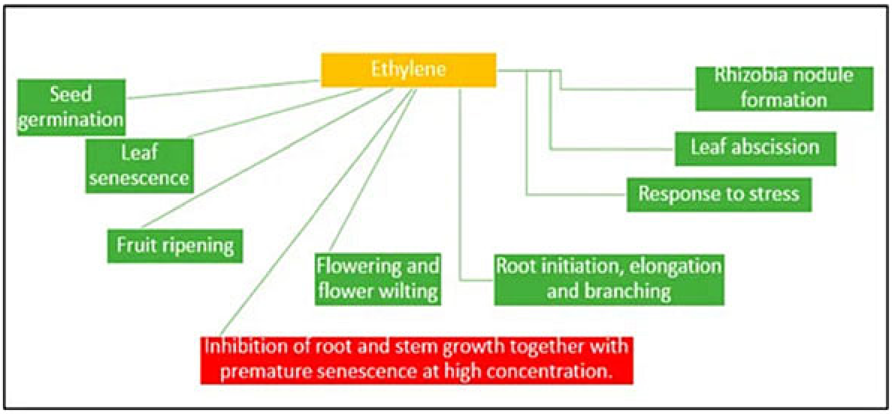

Fig. 2: Numerous distinct processes involved in a plant's growth and development are impacted by the phytohormone ethylene.

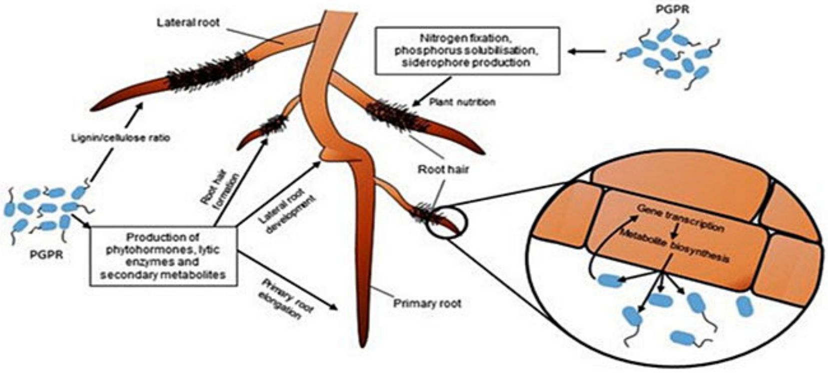

Fig. 3: shows one potential method through which plant growth-promoting rhizobacteria (PGPR) encourage plant growth. It is depicted where the processes of siderophore synthesis, phosphorus solubilization, and nitrogen fixation occur

Here, PGPR may abbreviate the deterioration cycle and rebuild a robust root system that could endure environmental stress by acting to degrade ACC, which is present in the rhizosphere. Additionally, Glick has demonstrated how microorganisms that make ACC deaminase and manufacture IAA may aid in plant growth. Rhizobacteria use the enzyme ACC deaminase as their main method of ethylene degradation. In salt-affected locations, Ahmad *et al.* (2013)[57] showed how ACC-deaminase-producing *Rhizobium* and Pseudomonas strains can improve the physiology, growth, and quality of mung beans. Despite being one of the major minerals found on the earth's surface, iron is not available to plants in the soil. Because iron is commonly seen in nature in the form of the extremely soluble Fe3+ ion, PGPR secretes siderophores to address this issue. Siderophores, which are tiny molecular weight proteins that bind iron, are used in the process of chelating ferric iron (Fe (iii)) from the environment. Microbial siderophores supply plants with iron when there is a lack of it, promoting their growth. According to Flores-Felix *et al.* (2015), a *Phyllobacterium* strain that produces siderophores encourages strawberry growth and quality. Here, siderophores released by the aforementioned PGPR are used by plants to sequester iron. Figure 2 depicts the anticipated flow of this manner of activity.

Volatile organic compounds (VOCs) are produced by a number of bacterial species from various genera, including *Bacillus*, Pseudomonas, Serratia, *Arthrobacter*, and Stenotrophomonas. The most well-known of these chemicals are acetoin and 2,3-butanediol, which *Bacillus* produces and which significantly enhance plant development. Other PGPR strains produce volatile organic compounds (VOCs) that may directly or indirectly increase plant biomass, disease resistance, and abiotic stress tolerance.[58]

Chitinase and glucanase are two examples of hydrolytic enzymes that would be procells, andduced as part of the procedure. Chitin and beta-glucan make up the majority of the components of a fungus' cell bacteria that produce chitinases and beta-glucanases would prevent fungi from growing. Chitinase and beta-glucanases are produced by Sino*rhizobium* fredii KCC5 and *Pseudomonas fluorescens LPK2*, which control the *fusarium* wilt caused by *Fusarium udum*. In addition to producing chitinase and beta-glucanases, *Rhizoctonia* solani and *Phytophthora capsici*, two of the most harmful crop diseases in the world, are inhibited by *Pseudomonas* spp.[59]

Consortium Preparation and Advantages

When compared to a crop that has not been infected, *rhizobium* inoculation helps increase nodulation, plant growth, and grain output by 10–15 percent. In the right circumstances, the bacteria *Azotobacter* and *Azospirillum* can improve plant growth and increase the output of a number of crucial crops in various soil types and climatic zones. Crop-specific biofertilizers include *Rhizobium*, *Blue Green Algae (BGA)*, and *Azolla*. Broad-spectrum biofertilizers include *Azotobacter, Azospirillum*, Phosphorus Solubilizing Bacteria (PSB), and Vesicular Arbuscular Mycorrhiza (VAM). When the biofertilizers were infected with a combination treatment of *Azotobacter* and *Azospirillum* as compared to when they were single inoculation plants, pearl millet, black pepper, and tomato plants showed substantially increased growth and grain yields.[60,61,62,63]

Similar improvements in growth and nutritional quality were also found in the case of Moringa oleifera using a combination of various biofertilizers, including *Azotobacter chroococcum*, *Azospirillum* braziliense, *Bacillus megatherium*, *Bacillus* circulans, *Pseudomonas fluorescens*, and *Saccharomyces cerevisiae.*[64] With the inoculation of *Azotobacter* and *Bacillus*, respectively, Kloepper and Beauchamp (1992)[65] observed enhanced wheat yields of up to 43 percent and 30 percent.

In symbiotic relationships with legumes and some non-legumes, such as *Parasponia*, *Rhizobium* plays an important role in fixing atmospheric nitrogen. The presence of legume crops in the field affects the population of *rhizobium* in the soil. The population declines when legumes aren't grown. To increase the number of productive strains of *Rhizobium* close to the rhizosphere and speed up N-fixation, artificial seed inoculation is frequently required. To produce functional nodules, each legume needs a particular species of *Rhizobium.*[66]

Studies have demonstrated that treating bean plants with *Rhizobium tropici* (glycogen synthase gene eliminated) led to an increase in nodules and plant weight. *Azospirillum brasilense* and *Pantoea dispersa* have been reported to enhance flavonoids and anthocynains in sweet pepper plants (*Capsicum annuum* L.) under low N supply while having no discernible impact on NO3 and total-N concentrations in the leaves. Additionally, strawberry plants inoculated with RC19 (*Bacillus simplex*), RC05 (*Paenibacillus polymyxa*), and RC23 (*Bacillus* spp.) showed higher soluble solid content (SSC) and vitamin C levels, indicating they may be able to increase yield and growth). According to one study, a biofertilizer made by combining PGPR and compost could improve plant growth and biocontrol.[67,68] Two PGPR that have been noted to be efficient biocontrol agents are *Bacillus* spp. and *Pseudomonas* spp. The most effective bacteria for eradicating plant diseases among them are *Bacillus subtilis*, *Bacillus amyloliquefacients*, and *Bacillus cereus*, in different ways. PGPR's capacity to produce endospores, particularly *Bacillus* spp. and *Pseudomonas* spp., makes it easier to create biofertilizer that is successful in various environmental situations.[69,70,71]

A sufficient rhizosphere for plant development and the biological conversion of nutritionally significant components, such as boosting the availability of N, P, and K and suppressing pathogen growth, are both made possible by the presence of sufficient densities of PGPR in biofertilizer. The increased availability of N, P, and K could increase soil fertility, improve the biocontrol abilities of antagonistic isolates, and increase the rates at which microorganisms can survive in soil.[71,72,73,74]

According to Sarma and Saikia (2014),[75] the *Pseudomonas aeruginosa* strain has enhanced *Vigna radiata* (mung bean) plant development in drought-prone environments. The size of the plant's stomatal openings determines how well it can use water for growth. The purpose of the stomata is to balance the water content of the leaf with root water intake. Ahmad *et al.* (2013)[76] and Naveed *et al.* (2014)[77] observed that under drought conditions, PGPR inoculated plants had higher stomatal conductance (water vapour departing through the stomata leaf) than non-PGPR injected plants. The results of the two investigations demonstrate that PGPR-inoculated plants typically increase their ability to use water efficiently. This discovery might be advantageous for the environment.

According to Marulanda *et al.* (2010),[78] inoculating maize roots with the *Bacillus megatertum* strain improved the root's capacity to absorb water in salty conditions. When *Pantoea agglomerans* was inoculated into the maize roots, Gond *et al.* (2015)[79] observed a similar pattern of behavior. They discovered that the maize root's capacity to absorb water under salty conditions had increased. Bacteria that can thrive in hypersaline environments will be more likely to colonize the external spaces and root rhizospheres of roots that are themselves exposed to high salinity conditions. Therefore, the aim was to check the bacterial isolates' capacity to grow in hypersaline environments first.

In vitro rooting of *Azospirillum brasilense* was employed by Gonzalez *et al.* (2015)[80] to increase the jojoba plant's resistance to salt during in vitro rooting. According to the results, *A. brasilense* can lessen the negative effects that saline circumstances have on jojoba roots. The bacteria reduced the impact of salinity on the jojoba plant's capacity to take root. This suggests that *A. brasilense* has a higher tolerance for salt stress than other plants.

Azospirillum has also been employed by Gabriela *et al.* (2015) to evaluate lettuce growth under salt stress. It has been demonstrated that giving the plant both *A. lipoferum* and B. megaterium as inoculants rather than only A. spirillum increased yield and provided the plant with balanced nitrogen and phosphorus nutrition. Compared to plants treated with either biofertilizer alone, plants co-inoculated with the phosphorus-solubilizing A. niger and the nitrogen-fixing *Azotobacter* performed better.[82]

Khan *et al.* (2012) established that the inoculation of biological nitrogen fixers utilizing *Azospirillum* and *Azotobacter* greatly boosted the growth, yield, and quality characteristics of chili (Capsicum annum L.), which is afflicted with plant parasitic nematodes. When compared to *Azotobacter, Azospirillum* performed better. The best growth, production, and quality metrics were obtained with simultaneous inoculation of biofertilizers (the maximum recommended dose of N-fertilizer at 100 kg N/ha and farmyard manure at 15 tons/ha). This reduces the need for nitrogenous fertilizers by 25% in the chili crop. Additionally, with dual inoculation with biological nitrogen fixers in addition to the advised full dose of nitrogen fertilizer, there were enhanced levels of plant nitrogen, phosphate, and potash, leaf chlorophyll, and residually accessible soil nitrogen, phosphate, and potash.[83]

The nematicidal effects of several bacterial biofertilizers, including nitrogen-fixing bacteria *Paenibacillus polymyxa* (four strains), phosphate- and potassium-solubilizing bacteria *Bacillus megatherium* (three strains), and tomato plants infested with the root-knot nematode *Meloidogyne incognita* in potted sandy soil, were measured by El-Haddad *et al.* It has been proven that co-inoculating some Pseudomonas and *Bacillus* strains with productive *Rhizobium* spp. increases chickpea growth, nodulation, and nitrogen fixation. Results from Mohammadi *et al.* (2010) showed that the application of phosphate-solubilizing bacteria, *Rhizobium*, and Trichoderma fungus together resulted in the maximum sugar, protein, starch, nodule weight, and nitrogen, potassium, and phosphorus contents of chickpea seeds. According to Shanmugam and Veeraputhran (2000), green manure and biofertilizer applications encouraged the growth of plants in rice that had more tillers and broader leaves, which may have been the cause of the increased leaf area. The betlevine produced more leaves after being treated with biofertilizer, which may be attributable to properly colonized roots, enhanced mineral uptake and uptake of water from the soil, and biological nitrogen fixation. According to Jeeva's research on bananas, it could also be attributed to the bacterium's production of IAA, gibberellins, and cytokinin-like compounds.[84]

Additionally, it is known that *Serratia liquefaciens* and *Pseudomonas putida* produce N-acyl-L-homoserine lactone (AHL) signaling molecules that improve tomato plants' systemic resistance to the leaf fungal disease *Alternaria alternata*. In a current study, it was discovered that *Burkholderia anthina* and *Pantoea agglomerans*, two phosphate-solubilizing bacteria (PSB), increased the growth characteristics of tomato plants under greenhouse circumstances when compared to the untreated control. It has also been demonstrated that *Azotobacter chroococcum* and *Pseudomonas fluorescens* can increase onion production's vegetative growth and yield by producing IAA, siderophores, and solubilizing tricalcium phosphate (TCP).[85]

Raj (2007)[85] stated that microorganisms (B. *subtilis,* Thio*bacillus thioxidans*, and *Saccharomyces* spp.) can be used as bio-fertilizers for the solubilization of fixed micronutrients like zinc. Soybean plants can fix atmospheric nitrogen through symbiosis, like many other legumes can. As a result, soybeans may meet 80–90 percent of nitrogen requirements. Agriculture can greatly benefit from bio-control, a contemporary disease management strategy. For the treatment of French bean root knot disorders, a BAU-biofungicide based on Trichoderma has shown promise. Mungbean root knot can be significantly reduced by using antagonist microorganisms like *Rhizobium* and *Bradyrhizobium*[86]

The growth, yield, and quality measurements of some plants greatly improved when biofertilizers using bacterial nitrogen fixers, phosphate and potassium solubilizing bacteria, and microbial strains of select bacteria were used.[87]

Limitations

The widespread use of this technology is restricted by a number of factors. Some of the potential causes include competition between the bioinoculant and the natural soil flora for niches, poor soil properties, environmental and soil pollution, extreme climatic conditions, the lack of an appropriate strain and an appropriate carrier material in the production unit, a lack of sufficient resources from public and commercial organizations, as well as a shortage of infrastructure for storage and transportation, among other things. Chemical fertilizers and biofertilizers never mix. Fungicides and plant ash are never sprayed at the same time as biofertilizers. Direct sunlight never touches biofertilizers. kept in storage at a temperature between 0 and 35 °C.[88]

Economic and Future Prospects

Microbial inoculants are used as a financial input to boost crop output, allowing for cheaper fertilizer doses and more soil nutrient uptake. Because more people are becoming aware of the benefits of biofertilizers for an expanding economy, the market for these products is always growing. The global market for biofertilizers was estimated to be worth $440 million in 2012, and it is projected to increase by 10% annually. Rhizobia is well-known for being employed as a biofertilizer, making up 79 percent of global demand, compared to biofertilizers that mobilize phosphate, which make up only 15 percent. The main market makers for biofertilizers are manufacturing firms and regulating government agencies.[89,90,91]

There are numerous businesses on the market that guarantee the safe manufacturing and delivery of biofertilizers. Still, there are some nations, such as those in Asia and Africa, that cannot access the newest agricultural technologies and are plagued by famine and malnutrition. Using biofertilizers, which are cheaply produced by small businesses and may be applied to limited agricultural regions, can have a substantial impact in this direction. In America, *Azospirillum* is a superb illustration of this; it may significantly accelerate plant development. They were instructed to develop and sell the most successful *Azospirillum* strains they had selected during numerous field tests. Today, there are more than 100 commercially accessible products made from *Azospirillum* strains that were developed primarily to increase agricultural yields of wheat, maize, and soybeans in South America. Similarly, 1 million hectares of land in India and 167 million hectares in China are used for organic farming.[92,93,94,95]

Conclusion

Using biofertilizers is a good way to boost crop output. In recent years, biofertilizers have been utilized to feed plants with the necessary nutrients and greatly improve their output. These are cost-effective and environmentally friendly; they give plants a natural environment, strengthen their immune systems, and shield them from harsh situations like dehydration and acidity. The benefits of using biofertilizers outweigh the drawbacks of using alternative, hazardous chemical fertilizers. The most significant microorganisms that are utilized as biofertilizers are discussed in this review, along with their mode of operation. The significant microorganisms *Azotobacter, Azospirillum*, *Phosphobacter*, and Rhizobacter are employed as biofertilizers. Recent advances in molecular biology, biotechnology, genetic engineering, microbial taxonomy, and nanotechnology have substantially benefited the development of biofertilizers with enhanced efficacy, greater competitive ability, and a diversity of characteristics. By minimizing or fully replacing the use of synthetic fertilizers with bio-fertilizers, environmental hazards are decreased, soil structure is improved, and agricultural pressure is increased. Biofertilizers are less expensive and have a large impact on cereal crop productivity. Up until now, the efficiency and excellence of agricultural products have been highlighted using monoculture systems that use certain agricultural microbes. Plant co-cultures or combination systems of microorganisms, however, may be more efficient at boosting soil microbial diversity, plant disease resistance, and vegetable crop output.

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Conflict of Interest

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