

Biofertilizers for sustainable agriculture in India

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Abstract

Biofertilizers are microorganisms that support the growth of plants by enhancing the nutrient supply to the host plant when given to seeds, plants, or the soil. Several microorganisms, including nitrogen-fixing soil bacteria, cyanobacteria, phosphate-solubilizing bacteria, molds, and mushrooms, are routinely utilized as biofertilizers. The most commonly used biofertilizers are nitrogen-fixers (N-fixers), potassium solubilizers (K solubilizers), phosphorus solubilizers (P solubilizer), and plant growth-promoting rhizobacteria (PGPR). Biofertilizers represent a secure and eco-friendly alternative to chemical fertilizers and pesticides, and reducing environmental pollution. Biofertilizers offers direct benefits such as increased crop yields, fruit quality, nitrogen fixation, phosphorus solubilization, improved plant growth, enhanced plant resistance to pests and diseases, reduced costs, improved soil vitality and soil properties, as well as enhancing and conserving natural resources. However, even with their promising future, the field of biofertilizers faces significant challenges related to formulation, quality control, storage, production, combined, which has prevented their widespread use.

Keywords: Biofertilizers; Sustainable agriculture; Soil health; Microbial diversity; Precision agriculture; Nutrient availability; Genetic engineering

1. Introduction

Global demand for agricultural products is increasing due to the increasing human population [1-55]. Food security is defined as the availability and accessibility of safe and nutritious food that fits the dietary requirements of a healthy and active lifestyle. To meet the challenges of food scarcity caused by the rise in population, various agricultural alternatives such as the use of chemical or synthetic fertilizers, pesticides, and insecticides have been used to produce crops with high yield within the shortest time possible and to protect them from insects and pest attack during and after harvest [1-6-50]. Soil structure has been damaged due to the accumulation of microplastics, use of chemical fertilizers and pesticides [1-7,8-50]. However, the use of these fertilizers and insecticides has raised much public concern about the sustainability, safety, and security of the food supply [1-7,8-55]. Studies have shown that there is a significant amount of pesticide residue present in food-stuffs long after they are taken away from farms for human consumption [9]. Daniel et al., (2022) [1] reviewed that there is an urgent need for alternatives such as biofertilizer in ensuring food safety and security [1-6]. Moreover, synthetic fertilizers that consist of various nutrients such as nitrogen (N₂), phosphorus (P), potassium (K), and sulphur may become harmful if used beyond the required amount [2]. The harmful effects of these fertilizers include the weakening of plant roots, the high rate of disease incidence, soil acidification, and eutrophication

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of ground water and other water bodies [1-11-55]. Nutrients such as nitrates leach to groundwater and cause “blue baby syndrome”, also called “acquired methemoglobinemia” [1-2-55].

The excessive use of chemical fertilizers to support intensive cropping is now known to alter the physical, chemical, and biological properties of soil, causing substantial soil degradation [1-20-56]. Chemical fertilizers have been shown to accelerate soil acidification, thereby disrupting the availability of various macro- and micronutrients and impeding plant growth [1-20-55]. Additionally, the usage of agrochemicals has been shown to cause the accumulation and concentration of mineral salts [1-20-56]. This leads to soil compaction, a condition that significantly reduces soil permeability and water availability and contributes heavily to soil erosion [1-40-56]. Furthermore, chemical fertilizers showed the natural distribution of soil microbiota by providing large quantities of certain elements such as nitrogen and phosphorus while adding little organic matter, limiting soil biodiversity and thus inhibiting key soil functions [1-41-56]. The impact of these chemicals will not only affect the present but also future generations. Therefore, there is need to search for eco-friendly approaches such as biofertilizers, which play a major role in sustainable agriculture [1-2-55]. Biofertilizers play a critical role in improving soil microbial diversity, enhancing soil structure, increasing organic matter content, and contributing to carbon sequestration [1-2-56]. Biofertilizer microorganisms colonize the rhizosphere or the inside of the plants. This entails the use of plant growth-promoting microorganisms that participate in a variety of biotic activities in the soil ecosystem in order to make it dynamic and sustainable for crop development [1-2-56]. Biofertilizers are widely used to accelerate microbial activities that increase the availability of nutrients that plants can easily absorb. They increase soil fertility by fixing atmospheric N₂ and solubilizing insoluble phosphates in the soil, resulting in plant growth-promoting chemicals [1-14-56]. Biofertilizer microorganisms that promote plant growth are involved in a variety of biotic activities in the soil ecosystem to keep it dynamic and sustainable for crop production [1-28-56]. They colonize plant roots competitively and improve plant growth through a variety of mechanisms, including phosphate solubilization; nitrogen fixation; production of indole-3-acetic acid (IAA), siderophores, 1-amino-cyclopropane-1-carboxylate (ACC) deaminase, and hydrogen cyanate; degradation of environmental pollutants; and the production of hormones, antibiotics, and lytic enzymes [1-33-56].

2. Biofertilizers in India

Biofertilizers in India are crucial, sustainable alternatives to chemical fertilizers, with production reaching over 164,000 tonnes of solid and 39,000 kilolitres of liquid formulations in 2024-25 [1-2-56]. Research indicates these eco-friendly microbial products (e.g., *Rhizobium*, *Azotobacter*) boost crop yields by 10-40% by enhancing nutrient uptake, soil fertility, and stress tolerance, supporting India's shift toward organic farming [1-2-56]. Biofertilizers, which contain living microorganisms, have emerged as a promising solution to mitigate the harmful impacts of traditional fertilizers on the environment [1-2-56]. The significance of biofertilizers in the Indian agricultural context is highlighted by the government's aggressive measures and the growing awareness among farmers. Forecasts for the worldwide biofertilizer industry are optimistic, predicting a sharp increase to USD 3.8 billion by 2025, led by biofertilizers that fix nitrogen [1-2-56]. Because of strict regulations on the use of chemical fertilizers, biofertilizers are the most widely used in Europe and Latin America. Because of its vast agricultural area and wise government regulations, the Asia Pacific region is clearly at the forefront of the use of biofertilizers [1-2-56].

Biofertilizers have emerged as a promising alternative to chemical fertilizers, contributing to sustainable agriculture by enhancing soil fertility, improving crop productivity, and minimizing environmental degradation [1-2-56]. These natural formulations containing beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, potassium-mobilizing bacteria, and mycorrhizal fungi promote nutrient availability through various mechanisms, including nitrogen fixation, phosphate solubilization, potassium mobilization, and organic matter decomposition [1-2-56]. Despite their numerous advantages, several challenges hinder their widespread adoption, including limited awareness, inconsistent performance under field conditions, and inadequate regulatory frameworks [1-2-56]. Variability in biofertilizer effectiveness due to environmental factors, carrier material selection, and poor formulation techniques remain significant barriers to their efficient utilization [1-2-56]. Recent advancements in biofertilizer technology, including the development of multi-functional biofertilizers, genetic engineering, and microbial consortia, have shown promising results in improving their efficacy [1-2-56]. Integrating biofertilizers with modern agricultural practices, such as precision agriculture, offers new opportunities for enhancing their performance and promoting large-scale adoption [1-2-56]. Effective policy support, training programs, and public awareness initiatives are essential for promoting biofertilizer usage among farmers [1-2-55]. Future research should focus on enhancing formulation techniques, conducting long-term impact studies on soil health, and establishing standardized guidelines for quality control [1-2-56]. Addressing these challenges will ensure the successful implementation of biofertilizer technology, contributing to agricultural sustainability and environmental protection [1-2-56]. These biofertilizers make use of the naturally available biological system of nutrient mobilization, which greatly enhances soil fertility and, as a result, crop productivity [1-2-56].

3. Advantages of Biofertilizers

Microbial inoculants, also known as biofertilizers, are organic products that contain specific microorganisms obtained from plant roots and root zones [1-2-56]. They have been found to boost plants' growth and yield by 10–40% [1-16-56]. These bioinoculants colonize the environment when applied to the rhizosphere and the interior of the plant to promote plant growth [1-17-35]. They not only add nutrients to the soil to improve soil fertility and crop yield, but they also protect the plant against pests and diseases. They have been shown to enhance seedling survival, extend the root system's life, eliminate harmful chemicals, and shorten flowering time [1-11-56]. Another advantage is that biofertilizers are no longer necessary after 3–4 years of continuous use, since the parental inocula are sufficient for growth and multiplication [1-18-56]. Plants require 17 essential elements for effective growth and development. N₂, P, and K are all required in significant amounts [1-18-56]. Several microorganisms, including nitrogen-fixing soil bacteria and cyanobacteria, phosphate-solubilizing bacteria, molds, and mushrooms, are routinely utilized as biofertilizers [1-19-56]. Similarly, microorganisms that produce phytohormones are used in the production of biofertilizers. They feed the plant with growth-promoting compounds such as indole acetic acid (IAA), amino acids, and vitamins, as well as improving the soil's productivity and fertility while conserving crop yield [1-20-56]. Plants are exposed to diverse microorganisms in their natural habitat, including bacteria, fungi, algae, and protozoa [1-26, 27-56]. The majority of these microorganisms occur in the soil's rhizosphere in various types of association, some as free-living organisms, while others associate with plant roots or even live within root or shoot tissues as endophytes [1-26, 27-56].

4. Types of Biofertilizers

Daniel et al., (2022) [1] reviewed that biofertilizers are divided into groups based on their functions and mechanisms of action [1-17-56]. The most commonly used biofertilizers are nitrogen-fixers (N-fixers), Frankia, Arbuscular mycorrhizal fungi (AMF), potassium solubilizers (K solubilizers), phosphorus solubilizers (P solubilizer), and plant growth-promoting rhizobacteria (PGPR), *Bacillus subtilis* [1-17-56]. One gram of rich soil can contain up to 10¹⁰ cfu bacteria, with a live weight of 2000 kg/ha [21]. The frequency of bacteria in the soil is influenced by the physical and chemical properties of the soil, organic matter, and phosphorus concentration, as well as cultural activities [1-17-56]. Nutrient fixation and improvements in plant growth by bacteria, on the other hand, are critical components for accomplishing future sustainable agricultural goals [1-26-56]. Microbes also help the ecosystem's numerous nutrient cycles [1-17-56]. *Desulfovibrio*, *Rhodospirillum*, and *Rhodopseudomonas* are examples of beneficial microbes that create symbiotic partnerships with plants, exchanging carbon-based photoassimilates for minerals ingested by the microbe [1-26-56]. Plant growth stimulators have also been found in other biostimulators, such as those found in seaweed extracts or decomposed vegetation [1-26-56].

5. Biological nitrogen fixation

Daniel et al., (2022) [1] reviewed that one of the most important nutrients for plant growth is nitrogen. Although our atmosphere contains around 80% gaseous nitrogen, green plants are unable to utilize it directly [1-36-56]. Biological nitrogen fixation is the conversion of atmospheric nitrogen to ammonia by soil-borne microbes [1-26-56]. About 175 × 10⁶ tons of nitrogen are fixed globally each year by nitrogen-fixing bacteria [1-37-56]. Biological nitrogen fixation is a critical component of microbial activities [1-37-56]. Only prokaryotes, which can be symbiotic or free - living in nature, are able to produce the nitrogenase enzyme to fix nitrogen biologically [1-37-56]. The enzyme nitrogenase catalyzes biological nitrogen fixation. Some soil bacteria and blue-green algae can convert nitrogen from the air into ammonia in their cells [1-37-56]. Diazotrophy, or nitrogen fixation, is the process of nitrogen reduction [29,37–40-56]. N₂ - fixers, also known as diazotrophs, are microbes that reduce atmospheric nitrogen [1-37-56]. Plants can directly utilize the ammonia produced [1-37-56].

The *Rhizobiaceae* (α -proteobacteria) are a family of symbiotic N₂-fixing rhizobacteria that live in a symbiotic association with leguminous plant roots [1-37-56]. This relationship necessitates a complicated interaction between the host and the symbiont, which leads to the creation of nodules that house the rhizobia as an intracellular symbiont [1-41-56]. The rhizobia include *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Azorhizobium*, and *Mesorhizobium* as a group [1-41-56]. Daniel et al., (2022) [1] reviewed that *Rhizobacteria* that fix nitrogen in non-leguminous plants are known [1-37-56]. In the instance of a symbiotic relationship with nitrogen-fixing bacteria in the root nodules of leguminous plants, these connections may be advantageous to the plant, while others may be parasitic, pathogenic, or have no known effect on plant growth or development [1-27-56]. Furthermore, some plant growth-promoting rhizobacteria may be able to stimulate additional particular plant growth-promoting properties, such as heavy metal detoxification, salinity tolerance, and biological control of phytopathogens and insects [1-34-56].

6. *Azospirillum*

Azospirillum is a Gram-negative, aerobic nitrogen-fixing bacteria that do not form nodules and belong to the *Spirilaceae* family [1-56]. Although there are several species in this genus, such as *Azospirillum amazonense*, *Azospirillum halopraeferens*, and *Azospirillum brasilense*, *Azospirillum lipoferum* and *A. brasilense* are the most beneficial [1-56]. Because they develop and fix nitrogen on the organic salts of malic and aspartic acid, *Azospirillum* forms associative symbiosis with many plants, notably those with the C4 dicarboxylic pathway (Hatch–Slack pathway) of photosynthesis [1-36-56]. As a result, it is mostly suggested for maize, sugarcane, sorghum, pearl millet, and other crops [1-36-56]. They make growth stimulants (IAA, gibberellins, and cytokinin) that help in root development and nutrient uptake (N, P, and K) [1-36-56]. Inoculation with *Azospirillum* has a significant impact on root development and exudation [1-56]. When *A. brasilense* sp. 245 was inoculated to maize, the production of various phytohormones increased noticeably, resulting in a significant increase in maize growth [1-16-56]. The root physiology and architecture of maize were altered as a result of the increased synthesis of several phytohormones, resulting in an increase in mineral intake by the plant [1-16-56]. Inoculation with *Azospirillum* and *Pseudomonas* altered the cultivable bacterial community in the wheat rhizosphere [1-149-56]. They also found that inoculating the soil microflora with *Azospirillum* and *Pseudomonas* altered the profiles of carbon source use during the tillering and grain filling stages [1-46-56]. Inoculation with two *A. brasilense* strains (40 and 42 M) isolated from maize roots was also found to affect the community-level physiological profiles of the cultivable microbial communities associated with rice [1-56].

7. *Azotobacter*

Azotobacter is a genus of non-symbiotic, free-living, aerobic, photoautotrophic bacteria belonging to the *Azotobacteriaceae* family [1-56]. *Azotobacter chroococcum* is the most frequent species in arable soils [1-56]. They are usually found in neutral and alkaline soils. *Azotobacter vinelandii*, *Azotobacter beijerinckii*, *Azotobacter insignis*, and *Azotobacter macrocytogenes* are among the other species identified [1-56]. They produce the Vitamin B complex and various phytohormones such as gibberellins, naphthalene acetic acid (NAA), and other compounds that prevent root infections while promoting root growth and mineral uptake [1-56]. *Azotobacter* has been found to release chemicals that limit the growth of certain root infections while also improving root growth and nutrient uptake [1-16-56]. *Azotobacter* has also been found to add 15–93 kg N/ha to *Paspalum notatum* roots [1-11-56]. Another strain, *Azotobacter indicum*, can produce a variety of antifungal antibiotics that are utilized to reduce seedling mortality by inhibiting the growth of many harmful fungi in the root region [1-6-56]. *Azotobacter* populations are often low in the rhizosphere of crop plants and in uncultivated soils, according to research [1-56]. This organism has been found in the rhizosphere of a variety of crops, including rice, maize, sugarcane, bajra, vegetables, and plantation crops [1-6-56].

8. Blue-Green Algae (*Cyanobacteria*)

The blue-green algae are photosynthetic organisms that belongs to eight different families. They promote plant growth by generating auxin, indole acetic acid, and gibberllic acid, as well as fixing nitrogen roughly 20–30 kg N/ha in submerged rice fields [1-56]. For lowland rice production, nitrogen is one of the main nutrients required in high quantities. Soil nitrogen and biological nitrogen fixation (BNF) by related microorganisms are the two main sources of nitrogen [1-43-56]. Fungi, liverworts, ferns, and flowering plants create symbiotic relationships with blue-green algae [1-45-56]. *Anabena oryzae*, *Nostoc calcicola*, and *Spirulina* sp. are three blue-green algae that have been shown to reduce the quantity of galls and egg masses induced by the root-knot nematode *Meloidogyne incognita* infecting cowpea, and to improve plant growth [1-16-56].

9. *Azolla*

Azolla has a 4–5% nitrogen content on a dry basis and 0.2–0.4% on a wet basis [1-16-56]. In rice production, it can be a valuable source of organic manure and nitrogen [1-56]. The important aspect of using *Azolla* as a biofertilizer is that it decomposes quickly in the soil and provides nitrogen to rice plants efficiently [1-16-56]. In addition, it adds to the provision of phosphorus, potassium, zinc, iron, molybdenum, and other micronutrients [1-56]. Prior to rice cultivation, *Azolla* can be utilized as a green biofertilizer in the fields [1-16-56]. *Azolla pinnata* is the most commonly used species in India, and it may be produced commercially through vegetative techniques [1-14-56]. *Azolla caroliniana*, *Azolla microphylla*, *Azolla filiculoides*, and *Azolla mexicana* are some of the other *Azolla* species that have been introduced to India for their huge biomass output [1-56].

10. Phosphate Solubilization

Despite the fact that phosphorus is abundant in the soil, the majority of it is insoluble and hence is inaccessible to support plant growth, since plants only absorb it in two soluble forms: monobasic and dibasic [1-16-56]. Inorganic phosphorus, such as apatite, or organic phosphorus, such as inositol phosphate (soil phytate), phosphomonoesters, and phosphotriesters, may be present [1-56]. Furthermore, much of the soluble inorganic phosphorus used in chemical fertilizers is quickly immobilized after being applied to the field. As a result, it is unavailable to plants and hence is wasted [1-16-56]. This has prompted researchers to look for environmentally benign and cost-effective ways to boost crop output in low-phosphorus soils [1-16-56]. Microbes that can solubilize inorganic phosphorus play a critical role in these settings as a potential option for providing phosphorus to the plants [1-16-56]. As a result, they are regarded as a promising biofertilizer, since they may provide the necessary phosphorus to plants, even from low-quality sources [1-14-56].

11. *Bacillus subtilis*

Bacillus subtilis is considered an essential industrial bacterium as it is widely used in biotechnology due to the improved expression and secretion of enzymes by the bacteria [1-40]. Besides, it is also used in food industries as flavour enhancers, sweeteners, and animal feed [1-40]. *Bacillus subtilis* is also used as a biofertilizer in India [57-61]. *Bacillus subtilis* role in root colonization, which triggers extensive reprogramming of plant gene expression, thereby integrating growth promotion with enhanced immune competence through a network that regulates plant-beneficial traits [1-61]. Its genomic regulation supports colonization, stress tolerance, and immune support, while synergistic interactions with other microbes highlight its adaptability [1-61]. As a versatile bio-fertilizer and biocontrol agent, further study of its strain-specific traits and rhizosphere interactions is key to maximizing its role in sustainable agriculture and forest control under environmental changes [1-61]. Among these beneficial microbes, plant-growth-promoting rhizobacteria (PGPR) represent a key functional group known to have the ability to enhance productivity and mitigate the impact of diseases through direct and indirect mechanisms [1-61].

12. *Frankia*: Nitrogen-fixing Actinobacterium

Frankia is a gram-positive nitrogen-fixing actinobacterium that forms a symbiotic association with actinorhizal plants. It is a filamentous free-living bacterium found in root nodules or in soil [62-67]. Due to the presence of resistant structure in culture, *Frankia* inoculum is easier to conserve than *Rhizobium* inoculum [62-67]. The genus *Frankia* has been classified in the order of *Actinomycetales* on the basis of morphology, cell chemistry, and 16S rRNA sequences [62-67]. Degraded lands are defined by soils that have lost primary productivity due to abiotic or biotic stresses [62-67]. Among the abiotic stresses, drought, salinity, and heavy metals are the main threats in tropical areas [62-67]. These stresses affect plant growth and reduce their productivity [62-67]. Nitrogen-fixing plants such as actinorhizal species that are able to grow in poor and disturbed soils are widely planted for the reclamation of such degraded lands [62-67]. It has been reported that association of soil microbes especially the nitrogen-fixing bacteria *Frankia* with these actinorhizal plants can mitigate the adverse effects of abiotic and biotic stresses [62-67]. Inoculation of actinorhizal plants with *Frankia* significantly improves plant growth, biomass, shoot and root N content, and survival rate after transplanting in fields [62-67]. *Actinorhizal* plants are nitrogen-fixing plants from 8 families including *Betulaceae*, *Casuarinaceae*, *Coriariaceae*, *Datisceae*, *Elaeagnaceae*, *Myricaceae*, *Rhamnaceae*, and *Rosaceae*, distributed in 25 genera and approximately 200 angiosperms species [62-67]. Generally, these nitrogen-fixing plants are able to grow in poor and disturbed soils and are well adapted to abiotic stresses such as drought, salinity, and flooding [62-67]. To reduce the transplantation shock during reforestation programs and to increase the productivity of these plantations, *Frankia* inoculation must be carried out during the nursery stage [62-67]. Association between actinorhizal plant and *Frankia* must be optimized by selecting a more efficient symbiosis [62-67]. The symbiotic microorganism *Frankia* significantly improves performance of actinorhizal plantations, it becomes very important to enhance *Frankia* production particularly in arid and semiarid areas for large-scale adoption by farmers [62-67].

13. Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) have been known for establishing symbiotic relationships with approximately 80% of terrestrial plant species [68, 69]. Due to their positive impact on soil organic-matter degradation and nutrient cycling, improving soil fertility, plant nutrition, water absorption, soil-aggregate stability, salinity, and drought-stress reduction, together with overall crop growth and productivity, can be employed as bioinoculants in sustainable agriculture [68, 69]. Therefore, AMF can be used as an amendment to enhance long-term soil fertility, plant nutrition, crop productivity, and yield quality, contributing to protection in agriculture and revival of agro-ecosystems [68, 69]. Moreover,

mycorrhizal-based products are often more cost-effective than conventional fertilizers, particularly in regions where phosphorus depletion in soils is present [68, 69]. In addressing the agricultural challenges posed by climate change, the use of biofertilizers, derived from living organisms, promotes environmentally friendly crop cultivation, and represents an adaptive strategy for sustainable agriculture in the face of climate uncertainty [68, 69]. Careful selection of the arbuscular mycorrhizal fungus (AMF) would represent a crucial step in mycorrhizal inoculation, considering the varying levels of compatibility between the AMF and the host plant [68, 69]. Biofertilizers are beneficial microbial inoculants derived from the rhizosphere that contain specific microorganisms [68, 69]. They are advocated as a secure partial alternative to replace chemical fertilizers and pesticides, offering cost effectiveness, eco friendliness, and easy farm-level production [68, 69].

14. *Trichoderma*

The use of *Trichoderma* as a biological agent could be cost-reducing and effective strategy. *Trichoderma* naturally present in most soils [70-74]. The genus *Trichoderma* comprises a great number of fungal strains that colonize plants roots as a symbiont and have properties to stimulate plant growth and development [70-74]. *Trichoderma* species have long been recognized as agents for the control of plant disease and for their ability to increase plant growth and development [70-74]. Commercialization of *Trichoderma* biofertilizer raises hope in farmers [70-74]. *Trichoderma* biofertilizer can be used in many crops such as groundnut, cotton, wheat, tobacco, Bengal gram, brinjal, sugarcane, eggplant, red gram, banana, tomato, sugarbeet, chillies, potato, soybean, citrus, cauliflower, onion, peas, sunflower, coffee, tea, ginger, turmeric, pepper, betel vine, cardamom etc [70-74]. Research on *Trichoderma* as a biofertilizer in India, particularly by the CSIR-National Botanical Research Institute (NBRI), showed that it is a dual-purpose agent that promotes plant growth and suppresses diseases while reducing greenhouse gas emissions (CO₂ and methane) [70-74]. Field studies in India (e.g., in UP and Shillong) demonstrated that *Trichoderma* enhances nutrient uptake, particularly phosphorus, zinc, and improves yields in rice, sugarcane, and vegetables [70-74]. *Trichoderma* used in almost all type of crops, with or without any amendments, but if *Trichoderma* biofertilizer is used as an amendment with compost may gives better results than any other fertilizer [70-74]. It minimizes the use of traditional fertilizer based on NPK. It improves the uptake of micronutrients to plants such as Cu, Zn, Fe, Na etc. and helps in solubilization of phosphate in soil and available to plants [70-74]. *Trichoderma* improves overall plant health, by creating a positive environment with symbiotic relationship with plants and releases various types of secondary metabolites including, growth hormones, endochitinase, proteolytic enzymes and benefits the plants by taking advantage of plant-microbe interactions [70-74]. The biofertilizer also used as soil conditioner, improves the population of plant beneficial microorganisms in soil [70-74]. It helps in mitigating green house gases like carbon dioxide and methane, a great cause for global warming (CSIR-India) [70-74]. *Trichoderma* is compatible with organic manure, and with biofertilizers like *Azospirillum*, *Rhizobium*, *Bacillus Subtilis* and *Phosphobacteria* [70-74]. *Trichoderma* species are considered opportunistic symbionts that are highly beneficial to plants [70-74]. While the majority of *Trichoderma* species are non-pathogenic saprophytes or beneficial symbionts in soil and plant ecosystems, a few can act as opportunistic pathogens in specific contexts, such as in immunocompromised hosts or under rare environmental conditions [70-74]. They enhance plant health through multiple mechanisms. In terms of biological control of plant diseases, *Trichoderma* has direct antagonistic actions against pathogens [70-74].

15. *Pseudomonas fluorescens*

Pseudomonas fluorescens is a versatile rhizobacterium used in agriculture as a biofertilizer and biocontrol agent to enhance plant growth, suppress soil-borne diseases (like *Fusarium* and *Ralstonia*), and improve nutrient uptake (phosphorus, iron) [75]. It stimulates root development via hormone production (IAA) and protects crops from environmental stresses like drought and salinity [75]. As an important plant rhizosphere growth-promoting bacterium, *P. fluorescens* mainly converts nitrogen in the air into a nitrogen source that can be absorbed and utilized by crops through its own nitrogenase secretion [75]. In addition, *P. fluorescens* can also secrete antibiotics such as phenazine-1-carboxylic acid, pyoluteorin, pyrrolnitrin, hydrogen cyanide, and 2,4-diacetylphloroglucinol to inhibit the growth of various pathogenic microorganisms, produce auxin, promote the increase in plant chlorophyll content, and produce forms such as glutathione and ACC deaminase to promote plant growth [75]. *P. fluorescens* has the characteristics of simple nutritional requirements, fast reproduction, and strong competitive colonization ability, and has enormous application potential in agricultural production as a biofertilizer [75].

16. Conclusion

The continuous rise in the global population has translated to a direct increase in the demand for food production. In light of the harmful effects of chemical or synthetic fertilizers, biofertilizers are supposed may be a safe alternative to

chemical inputs and minimize alteration of the ecosystem to a great extent. Therefore, soil has lost the fertility and most of the agricultural produce consumed is not safe because of the chemical residues that are left in them. Biofertilizers are cost-effective, eco-friendly in nature, and their prolonged use enhances soil fertility. It has been found that using biofertilizers increases crop yield by 10–40% by increasing protein, vital amino acids, vitamins, and nitrogen fixation. Biofertilizers provide a number of advantages, including being a low-cost source of nutrients, excellent suppliers of micro-compounds and micronutrients, organic matter suppliers, growth hormone producers, and a means of counteracting the negative effects of chemical fertilizers. Different microorganisms are important components of soil, and they play a key role in a variety of biotic activities in the soil ecosystem that keep the soil active for nutrient mobilization and long-term crop development. The use of these biofertilizers has been reported to boost the food production rate, and they are a safer farm product for consumers. Hence, biofertilizers remains a better alternative for producing safer crops and enhancing global food security.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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