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The Role of Biofertilizers in enhancing soil and Productivity - A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Biofertilizers, which provide a natural and green alternative to chemical fertilizers, are crucial to sustainable farming techniques. Through strategies such as nitrogen fixation, phosphate solubilization, and the enlargement of soil microbial variety, those microorganism-derived compounds improve soil fertility and sell plant boom. This evaluation explores the definition and kimportance of biofertilizers, highlighting the variations among chemical fertilizers and organic nitrogen fixation. It categorizes biofertilizers into diverse sorts, inclusive of nitrogen-solving, phosphate-solubilizing, and mycorrhizal biofertilizers, and discusses their ecological benefits. The impact of biofertilizers on ecosystem fitness and soil reclamation of degraded lands is likewise tested, showing their position in restoring soil structure and fertility. Various application strategies,

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along with seed inoculation, soil remedy, and foliar sprays, are mentioned to maximize their effectiveness. Although biofertilizers have many advantages, along with the effectiveness of fees, sustainability inside the environment, and better crop yields, additionally they have drawbacks, along with issues with soil compatibility and shelf-existence. Finally, rising views on biofertilizers spotlight improvements in biotechnology and their ability to play a pivotal role in weather-clever and resilient agriculture. This assessment underscores the growing importance of biofertilizers as a sustainable answer for current agricultural demanding situations.

Keywords: Biofertilizers; microbial organisms; soil health; sustainable agriculture.

1. INTRODUCTION

The importance of agriculture is very good in helping global food security and reducing diet challenges. In this context, the implementation of the Biofertilizers is a promising approach to improve agricultural efficiency in a permanent way (Albahri, et al*.,* 2023). The integration of biological agents as substitutes for chemical fertilizers has resulted in notable enhancements in various crop parameters. In the context of the twenty-first century, challenges such as climate change, food insecurity, and agricultural pollution pose significant threats, adversely affecting plant growth, soil health, and food availability. To tackle these pressing issues, innovative methodologies are required, as numerous stressors—including toxic heavy metals, organic pollutants, emerging contaminants, and a range of biotic and abiotic factors—can hinder nutrient accessibility, disrupt plant metabolic processes, and diminish crop yields and soil fertility. Among the various strategies being investigated to bolster plants000 resilience to environmental stressors, nanotechnology, particularly the use of nanoparticles, demonstrates considerable potential in enhancing plant performance under challenging conditions. This technology is set to transform both agriculture and pharmaceuticals, promising a more sustainable, efficient, and resilient system for both sectors. Specifically, nano-fertilizers are anticipated to improve nutrient utilization efficiency in plants through a controlled and sustainable release of nutrients (Sujanya and Chandra, 2011) (Mariyam, et al*.,* 2024) (Pathak, et al*.,* 2024). Biofertilizers are crucial for environmental conservation, as they enable a lower dependency on chemical fertilizers in the cultivation of crops in diverse regions. These products are characterized by the inclusion of naturally occurring microorganisms that are artificially multiplied to improve the fertility of the soil and boost productivity of crops (Mazid and Khan, 2014). Chemical fertilizers negatively impact the health of soil, causing a decline in organic matter levels, reduction in the ability to hold onto water, alterations in soil fertility, heightened salinity, compromised nutrient uptake, and disturbances in soil structure and microbial diversity. The enduring nature of these harmful chemicals poses a considerable threat, leading to the pollution of groundwater resources (Savci, 2012). In the pursuit of self-sufficiency, nations have extensively employed chemical fertilizers to enhance agricultural productivity. Nevertheless, the application of these fertilizers has led to significant environmental degradation, as they diminish the soil's water retention capabilities, adversely affect its fertility, elevate soil acidity, and decrease microbial populations, ultimately causing nutritional deficiencies within the soil (Nosheen, et al*.*, 2021). Biofertilizers serve as valuable tools within the agricultural ecosystem by improving soil quality through the addition of essential components such as nitrogen, vitamins, proteins, and enhanced water retention capabilities, thereby mitigating the adverse impacts associated with chemical fertilizers (Mariya and Sripriya, 2023). Soil serves as a crucial basis for meals production at some point of human history. However, in current many years, the enormous adoption of agricultural practices, such as the application of pesticides and synthetic fertilizers, which have ended in huge degradation of soil on a worldwide scale. This degradation has resulted in diminished fertility, on the whole due to a decline within the field of biodiversity, reduced retention of water capabilities, in conjunction with disruptions in cycles of biogeochemistry. The intricate relationships that exist between plants, soil, and microbes have a significant impact on soil health and plant output. (Harman, et al*.,* 2021).

The Soil microorganisms engage in cooperative interactions both among themselves and with plant roots through various mechanisms, contributing significantly to a range of essential functions that are crucial for maintaining ecological equilibrium within the soil (Kumar et al*.,* 2021). It has been noted that utilizing Apricot biofertilizers farming alters the microbiological structure and deterioration mechanisms, which might lead to more effective nutrient cycling in soil environments during field cultivation (Baldi, et al*.,* 2021) (Agri, et al*., 2*021). The integration regarding biofertilizers into agricultural practices may provide an effective means to bolster the microbial status of soil, facilitating the activity of the natural soil microbiota and thereby impacting nourishment availability and the degradation of natural materials. (Chaudhary, et al*.,* 2021). The interactions between plant life and microorganisms can be classified as beneficial when they decorate plant survival, nutritional high-quality, and agricultural yield. In contrast, they are deemed detrimental if they hinder growth of plants. Fertility of soil fundamentally connects to the equilibrium between microbes and plant life (Vishwakarma, et al*.,* 2021). Regular use of chemical fertilizers is often deemed unsustainable, as it can adversely affect soil ecosystems. Such practices may additionally cause a decline in soil biodiversity and growth in soil acidity, mainly from nitrogen fertilizers that decrease pH degrees. This change can destabilize soil aggregates, making them more vulnerable to erosion, which in flip can cause a lower in soil fertility. As a result, even with the continued application of chemical fertilizers, agricultural productivity may suffer over time (Nyalemegbe, et al*.,* 2009).

Comparison Between Chemical and Biological Nitrogen Fixation: The contribution of biological nitrogen fixation of (BNF) to nitrogen usage in agriculture is significant, comprising 65% of the total consumption. (Burris and Roberts, 1993). In numerous agricultural systems, nitrogen frequently serves as the primary limiting nutrient that influences crop yield. Although nitrogen is abundant in the atmosphere, plants are unable to utilize it in its inert form. The availability of nitrogen is facilitated through fertilizers, which are produced via the atmospheric nitrogen chemically fixed by the Haber-Bosch method. This method necessitates elevated temperatures (ranging from 400 to 500°C) and substantial pressure (approximately 20 MPa), resulting in energy requirements equivalent to 5.5 barrels of oil, 2 metric tons of coal, or almost 875 cubic meters of natural gas to synthesize ammonia in one metric ton. The Dinitrogen is characterized as the diatomic molecule with the highest stability, with two nitrogen atoms connected through a robust triple bond. The energy required to dissociate this triple bond is significant (945 kJ), presenting a considerable challenge in the process of dinitrogen fixation (Dixon and Wheeler, 1986). Global nitrogen cycle indicates that each and every nitrogen atom found in the atmosphere completes a full cycle roughly once every million years. (Postgate, 1990) Atmospheric dinitrogen can be biologically fixed by diazotrophs, which are prokaryotic organisms capable of converting dinitrogen into ammonia. This ammonia becomes accessible to crop plants. In the soil, some microorganisms facilitate the transformation to the nitrate to ammonia, which is later available to the plant sharp. The produced nitrate can undergo Denitrification processes in deep soil layers, resulting in nitrogen gas left back in the atmosphere. This sequence illustrates the typical nitrogen cycle. The enzymatic determination of nitrogen with bacteria is at normal pressure and temperature, a process called biological nitrogen determination (BNF). Determination of natural nitrogen fixation in the biosphere presents challenges, it is considered about 10 million tonnes per year, unlike about 160 million tonnes per year from anthropological sources, which are 1.5 times higher than natural fixation. (Galloway et al*.,* 2008).

Biofertilizers: The concept of Biofertilizer's in India is specifically associated with fertilizers that provide essential nutrients to crops through microbiological means, although other countries may refer to this concept using different terms. Microbial-based fertilizers, commonly termed biofertilizers, play an essential part of sustainable farming, significantly contributing to the long-term enhancement of soil fertility (Bargaz et al*,* 2018). Biofertilizers, which are commonly called microbial inoculants, consist of organic products that include specific microorganisms extracted from the root systems and adjacent zones of plants. Evidence suggests that their application can lead to an increase in plant growth and yield by 10% to 40% (Kawalekar, 2013). Biofertilizers are typically utilized in solid or dry formats, which are formulated by incorporating them into appropriate carriers, including lignite, humus, wood charcoal, rice bran, peat, clay minerals, and wheat bran. The use of these carriers extends the durability of the products and simplifies the management of microbiological agents. (Bhattacharjee and Dey, 2014). Biofertilizers consist of organic fertilizers that originate from biological sources, including both plant and animal origins, as well as living or inactive microbiological cells. They possess the ability to increase the accessibility and bioavailability of nutrients, thereby facilitating their uptake by plants (Lee et al*.,* 2018).

Bioinoculants that inhabit the rhizosphere promote growth and the internal structures of plants enhance growth when introduced to seeds, plant surfaces, or soil (Rahuwanshi, 2012). Biofertilizers are defined as natural materials that encompass living microbes, such as *algae*, *fungus*, and *bacteria*, or their byproducts. These substances are utilized in agricultural practices by applied to the soil, seeds, or the surfaces of plants to get better soil fertility and stimulate plant development (Alnaass et al*.,* 2023). In the context of natural fertilizers, unique organisms, including earthworms, play important position in converting those fertilizers into materials that flowers can effortlessly absorb. Plant-increase promoting rhizobacteria are the maximum usually hired bacteria inside the manufacturing of biofertilizers, as they sell plant increase thru the release of potassium (K), nitrogen fixation (N), phosphorus solubilization (P), and hormone manufacturing (Lu, et al*.,* 2020). Advantageous microbes, together with numerous microorganism and fungi, colonize the rhizosphere, which is the soil region being laid low with root exudates, in addition to the surfaces of vegetation, thereby establishing either symbiotic or associative interactions with them (Ayala and Rao, 2002). Biofertilizers operate via enhancing the absorption of vitamins, facilitating the fixation of atmospheric nitrogen, solubilizing phosphates, and mobilizing various different vitamins, which collectively beautify the accessibility of essential vitamins for plant improvement (Bhardwaj et al*.,* 2014). Biofertilizers make contributions definitely to soil fitness, beautify the physical shape of the soil, and aid a numerous microbial community within soil environment. They present an environmentally sustainable opportunity to chemical fertilizers, encouraging practices that promote sustainability in agriculture while concurrently lowering environmental pollutants and lessening dependence on synthetic agricultural inputs. (Daniel et al*.,* 2022).

Categories of Biofertilizers: Different kinds of biofertilizers may be prominent by their distinct roles and modes of movement. The maximum generally used biofertilizers consist of rhizobacteria that sell plant boom, nitrogen-solving shops (N-fixers), potassium-solubilizing microorganisms (K-solubilizers), and phosphorus-solubilizing organisms (P-solubilizers) and (PGPR) (Mahdi et al.,2010). Among the mechanisms that outline the direct effects on plant life are nitrogen fixation, phosphate compound solubilization, micronutrient solubilization, and phytohormone manufacturing. (Chaudhary et al., 2021). One gram of fertile soil might also moreover include as many as 10^10 microorganism, contributing to a biomass of about 2000 kg steady with hectare (Raynaud and Nunan, 2014). “Biofertilizer" is an umbrella time period that consists of loads of materials, which encompass nitrogen-fixing microorganisms, phosphorus and potassium solubilizers, mycorrhizae, and several microbial consortia. These entities are frequently known through different labels, which include microbial injections, bioinoculants, soil injections, microbial fertilizers, bioenhancers, phytostimulators and Plant Growth Promoting Rhizobacteria, among others. Despite the attractive prospects offered by biofertilizers, commercially produced microbial-based variants confront numerous obstacles in real-world agricultural situations. These challenges are primarily attributed to the survival rates of these microbial inoculants under fluctuating environmental circumstances, insufficient awareness among farmers, poor formulation quality, and the lack of localized strains that perform effectively. (Mitter et al*.,* 2020). Soil bacteria can exhibit various morphological forms, including cocci (spherical, 0.5 μm), bacilli (rod-shaped, 0.5–0.3 μm), and spiral configurations (ranging from 1 to 100 μm). The distribution of these bacteria within the soil matrix has an impact on the soil' s and chemical characteristics, the presence of organic matter, phosphorus levels, and agricultural practices. Notably, the development of sustainable agricultural methods in the future depends on the functions of bacteria in nitrogen fixation and plant growth stimulation additionally, these microbes play a crucial role in facilitating diverse nutrient cycles within ecosystem.

Types of Nitrogen-Fixing Biofertilizers: The maximum crucial thing proscribing plant growth is the provision of nitrogen. (Gupta et al., 2012). Biological fixation of nitrogen is the technique with the aid of which di-nitrogen (N_2) is converted right into a shape that may be used by flowers, broadly speaking ammonium (NH_4). This transformation involves the reaction of N_2 with hydrogen ions derived from water. It is vital to observe that nitrogen fixation is not exclusively a biological method; natural phenomena inclusive of lightning and fire also can convert N_2 into nitrate ($NO^-{}_3$). In truth, about 1% of the whole nitrogen constant annually is attributed to ammonia produced by using lightning (Igarashi and Seefeldt, 2003). Although nitrogen makes up around 80% of the environment in its free form, most vegetation cannot at once soak up this nitrogen. It takes a sure set of microbes to allow plants to use nitrogen from the ecosystem. These microbes are known as organic nitrogen fixers (BNFs) due to the fact they rework inert nitrogen dioxide into natural shape that flowers can absorb. Although nitrogen makes up round 80% of the surroundings in its unfastened shape, maximum vegetation cannot right away soak up this nitrogen. It takes a positive set of microbes to permit plants to use nitrogen from the ecosystem. Biological nitrogen fixers (BNFs) are microorganisms that rework inert nitrogen dioxide into an organic form that flowers can absorb. (Reed et al., 2011). All dwelling organisms, encompassing every Eukaryotes and Prokaryotes, inherently rely upon natural nitrogen fixation (BNF) for their nitrogen deliver, whether or not without delay or in a roundabout manner. Proteins, nucleic acids, and other natural nitrogenous substances are all synthesized the usage of nitrogen as a fundamental issue. Process of biological nitrogen fixation is energetically annoying, necessitating the cons. Below, an overview of the principal nitrogen-fixing bacteria is provided.

Rhizobium: Rhizobium is classified inside the bacterial circle of relatives *Rhizobiaceae* and serves as a prime example of symbiotic nitrogen fixation. This bacterium is capable of solving atmospheric nitrogen (N_2) in each leguminous and non-leguminous vegetation. According to investigate, Rhizobium can restoration nitrogen at as much as 300 kg N/ha/year for a number of legume species (Pindi and Satyanarayana, 2012). Within the α-proteobacteria, *Rhizobiaceae* circle of relatives includes symbiotic nitrogen-solving rhizobacteria which infect leguminous plant roots. Establishment of this symbiotic dating entails complex interactions between the host and microorganism, main to the formation of nodules wherein Rhizobia act as intracellular symbionts (Allito, et al., 2015). Rhizobia is the collective call for the genera *Rhizobia*, *Bradyrhizobia*, *Sinorhizobia*, *Azorhizobia*, and *Mesorhizobia*. Additionally, there are diazotrophs—non-symbiotic rhizobacteria that recuperation nitrogen in non-leguminous species—which could engage with their host flora in a non-obligate way. (Verma et al*.,* 2010). Upon infecting roots of leguminous plants, bacteria induce development of nodules. Inside these structures, molecular nitrogen undergoes reduction to ammonia, which plant employs for manufacturing of vitamins, proteins, and other substances high in nitrogen. Consequently, these root nodules act as ammonia manufacturing sites. (Flores-Félix et al*.,* 2013). The species of *Rhizobium* enhance growth of non-leguminous plants by causing alterations in root structure and physiological growth processes. Rhizobium application has been demonstrated to enhance crop development by raising nitrogen content, plant height, seed germination rates, and leaf chlorophyll levels. (Sara et al*.,* 2013). Rhizobium is frequently employed in agricultural practices to secure sufficient nitrogen, with around 80% of biologically fixed nitrogen originating from symbiotic relationships, thereby presenting an opportunity to substitute chemical nitrogen fertilizers (Rubio-Canalejas et al*.,* 2016).

Frankia—Casuarina: *Angiosperms* from various genera, including *Hippophae, Discaria, Coriaria, Myrica, Alnus, and Casuarina*, establish symbiotic connections to *Frankia*, an actinomycete. On many plant species in 25 genera and 8 families of dicotyledons, these filamentous, spore-forming actinomycetes create nodules. These plants are all classified as woody trees or shrubs. Such symbiotic relationship plays important part in improving economy of nitrogen through fixation of nitrogen and is crucial for agroforestry systems as well as for preserving deteriorating land surfaces. It is known that *actinorhizal* symbiosis improve temperate forest's fertility in a manner similar to contributions of woody legumes in tropical regions. Actinorhizal plants thrive in nitrogen-deficient environments, such as eroded slopes and mining waste sites, and they yield commercially valuable shrubs and large trees. In North America, the current grasslands lack a substantial legume presence, indicating that *actinorhizal* symbiosis historically contributed significantly to the enhancement of nitrogen levels in these areas. The actinorhizal nodules consist of groups of altered roots containing Cells infected with *Frankia* found within the cortex. Initially, nodules manifest as swellings, which subsequently develop into lobes at their tips, forming vesicles that serve as the locations for fixing nitrogen. Frankia's capacity for biological nitrogen fixation (BNF) in Coriaria arborea is roughly 90 kg N/ha/year. (Silvester, 1976).

Anabaena Azollae: Angios-Azolla serves as a biofertilizer in rice cultivation across various countries, including the China, Vietnam, Thailand, Sri Lanka, and Philippines. Water fern Azolla forms a symbiotic interaction with cyanobacterium Anabaena azollae. Azolla in India is diagnosed as treasured biofertilizer for paddy fields, and farmers use it drastically. It grows well in water beds or slow-moving creeks and is applied on crops in between rice plantings. Following a growth period, it is either incorporated into the soil prior to transplanting or allowed to decompose as the canopy of rice develops. Due to its low carbon-to-nitrogen (C:N) ratio, *Azolla* is rapidly mineralized, providing essential nitrogen to the plants. In addition to nitrogen fixation, Azolla effectively suppresses weed growth in wetland rice, offering an economic advantage of rice farming. Azolla has also recently been used as animal feed to increase dairy animal's milk production. It has been demonstrated that applying 15 tons of Azolla microphylla per hectare in conjunction with neem cake increases grain output by 29.2%. (Sundaravarathan and Kannaiyan, 2002). Azolla leaves exhibit a nitrogen composition of 4-5% when calculated based on dry weight, in contrast to a nitrogen content of 0.2-0.4% when considered according to wet weight. These leaves break down quickly, releasing nitrogen that is beneficial for plant growth. *Azolla-Anabaena* symbiotic system is capable of supplying 1.1 kg of nitrogen daily per hectare, with a single crop of *Azolla* supplying between 20 and 40 kg nitrogen per hectare to rice crops over a period of approximately 20 to 25 days (Setiawati et al*.,* 2018).

Azotobacter: Azotobacter, that's a part of *Azotobacteriaceae* own family, is employed for all non-leguminous vegetation as a biofertilizer, specifically the ones which include rice, cotton, candy potatoes, candy sorghums, veggies, and sugarcane. Azotobacter chroococcum is most common species in cultivated soils, and these organisms are normally determined in alkaline and neutral soil settings. (Moraditochaee et al*.,* 2014). Azotobacter is a diazotrophic bacterium that exists independently and is capable of solving nitrogen. Its diverse metabolic activities make a contribution extensively to nitrogen cycle (Sahoo et al., 2014). Azotobacter is accountable for biosynthesis of crucial plant hormones, which include Vitamin B complex, naphthalene acetic acid, gibberellic acids, and indole acetic acids. These hormones make contributions to suppression of root pathogens, promotion of root growth, enhancement of mineral uptake, and development of soil fertility (Sumbul et al., 2020*).* It has been noted that Azotobacter is typically not very abundant in the rhizosphere of crop plants or in uncultivated soil. This organism's presence has been observed in the rhizospheres of multiple crop types, including Bajra, rice, maize, and sugarcane, selection of plantation crops and vegetables (Wani et al*.,* 2013). Azotobacter possesses capability to synthesize vitamins like riboflavin and thiamine (Revillas et al*.,* 2000). Genus Azotobacter is capable of producing antifungal substances and antibiotics that suppress the growth of numerous pathogenic fungi in root area, which plays a significant role in mitigating seedling mortality (Bhosale et al*.,* 2013).

Azospirillum: The genus *Azospirillum* consists of Gram-negative, aerobic bacteria with the capacity to fix nitrogen that don't form nodules. These organisms are categorized within the *Spirilaceae* family (Mehnaz, 2015). The genus contains a whole lot of species, together with *Amazonian*, *Azospirillum*, *Azospirillum halopraeferens*, and *Azospirillum brasilense*; but most goodsized positive species are *Azospirillum brasilense* and *Azospirillum lipoferum* (Mishra et al., 2013). *Azospirillum lipoferum* is customary bacterium located in soil, first diagnosed by Beijerinck in 1925. This bacterium is classed as associative symbiotic nitrogen-fixing organism, regarded for its manufacturing of materials that promote development, like indole-three-acetic acid (IAA) and gibberellins, which decorate root development. Additionally, *Azospirillum lipoferum* synthesizes sizable amounts of plant boom-promoting substances, which include pantothenic acid, thiamine, and niacin, which make contributions to stepped forward plant increase and yield. Notably, Azospirillum exhibits remarkable versatility in its ability to fix atmospheric nitrogen (Dobereiner, 1997). Azospirillum forms a symbiotic relationship with a range of plants, particularly those that use the C4 dicarboxylic route (also known as the Hatch-Slack pathway) for photosynthesis, as it thrives and fixes nitrogen in presence of organic salt's derived from aspartic and malic acids (Mishra and Dash, 2014). Consequently, it's far in general counseled for cultivation of vegetation such as Pearl millet, sorghum, sugarcane, and maize. These organisms produce growth-selling chemical compounds, together with gibberellins, cytokinins, and indole-3-acetic acid (IAA), which resource in root development and uptake of critical plant vitamins like potassium (K), phosphorus (P), and nitrogen (N). The inoculation of Azospirillum notably impacts root increase and exudation procedures (Trabelsi and Mhamdi, 2013).

Glucanobacter: Acetobacter diazotrophicus, a notable diazotroph, serves as nitrogen-fixing bacterium located in stems, roots, and leaves of sugar beet and sugarcane plants, and introduced through treatment of soil. Furthermore, it produces growth-promoting compounds including indole-3-acetic acid (IAA), which facilitate root development, seed germination, and nutrient absorption. (Gahukar – 2005-06). This organism exhibits a remarkable tolerance for elevated levels of sucrose and thrives endophytically within sugarcane ecosystems. In Presence of hormones that promote growth, specifically indole-3-acetic acid (IAA), released by plants facilitates germination and root development, thereby enhancing nutrient uptake. Consequently, this bacterium is capable of fixing approximately 15 kg of nitrogen per acre on annual basis. The distribution of different types has also evolved, with phosphate-solubilizing bacteria (PSB) demonstrating significantly superior results compared to Azotobacters, which show moderate performance. The overall quantity of units diminishes the annual capacity, while the decline in rhizobium populations indicates that production of groundnuts and pulses did not meet anticipated levels. The correlation between capacity and actual distribution, as opposed to mere production, provides a metric for assessing capacity. Furthermore, the relationship between actual distribution and capacity offers insights into the extent of capacity utilization. Notably, the most significant enhancements in straw and grain yield were recorded in wheat plants that received rock phosphate as a phosphorus fertilizer, following inoculation with a combination of Azotobacter, Rhizobium, and vesicular-arbuscular mycorrhizae (VAM). Gluconacetobacter diazotrophicus serves as nitrogen-fixing endosymbiont in sugarcane plants, where it exerts antagonistic effects on *albilineans xanthomonas* by inhibiting synthesis of bacterial polysaccharide known as xanthum. In the case of soybean and cereal vegetation, those plant life can derive as masses as 30% in their nitrogen necessities through biological nitrogen fixation (BNF), in particular while furnished with enough phosphorus, potassium, and trace factors. Among those flora, sugarcane demonstrates most top notch advantage, capable of acquiring as much as 150 kg of nitrogen steady with hectare through BNF. (Dobereiner, 1997)

Cyanobacteria (Blue-Green Algae): Cyanobacteria that restoration nitrogen are most sizeable category of nitrogen (N_2) fixers determined on Earth. This diverse assemblage of prokaryotic organisms, generally called among blue-green algae are, includes genera along with *Lyngbya*, *Oscillatoria*, *Nostoc*, *Anabaena*, and *Aulosira* (Sharma et al*.,* 2010). Cyanobacteria set up symbiotic relationships with various organisms, consisting of ferns, flowering vegetation, liverworts, and fungi (RoyChowdhury et al*.,* 2014). Cyanobacteria's function in soil fitness is important, as they increase soil with nitrogen and offer vital vitamins, which include increase-selling and nutrition B complicated substances which includes Gibberellic acid, indole acetic acid, and auxins, that are instrumental in accelerating plant increase. In submerged rice fields, those microorganisms can restoration nitrogen at quotes of 20 to 30 kg in step with hectare, ensuing in a yield boom of 10 to 15 percent whilst implemented at 10 kg in step with hectare. Research findings display that integration of blue-inexperienced algae a in agricultural systems, especially in context of rice cultivation, complements the nitrogen deliver for plants. (Singh et al*.,* 2016) (Mishra and Pabbi, 2004). The lines validated the potential to launch bioactive compounds, which contributed to progressed plant boom and improved yield. Additionally, a separate investigation revealed that the inoculation of rice with cyanobacteria sourced from rice fields positively influenced both the rice plants and characteristics of soil (Roona and Shamina, 2022).

Phosphate Solubilizing and Mobilizing Biofertilizers: Plants typically contain approximately 0.2% phosphorus based on dry weight, which is a crucial nutrient for their development and growth. Among macronutrients, phosphorus is generally least mobile nutrient obtainable by plants in most soil environments. The conversion of insoluble phosphate forms into soluble form is facilitated with help of microbes (Prabhu, et al., 2019) (Kalayu, 2019). Phosphate-solubilizing microorganism (PSB) play important role in transform phosphate compounds that are insoluble, like as H_2PO_4 and HPO_4, into soluble forms through numerous mechanisms. These mechanisms include secretion of acids that are organic, chelation processes, and exchange reactions between ions. Within microbial communities, PSB represent approximately among 1–50% of the whole microbial population engaged in phosphate solubilization, in contrast to fungi, which contribute simplest 0.1–0.5% to those activities (Sharma et al., 2013). Various microorganisms, inclusive of *Bacillus*, *Rhizobium*, *Aerobacter*, *Burkholderia*, *Aspergillus*, and *Penicillium*, are recognized as phosphate-solubilizing bacteria and fungi. The utility of

Alcaligenes sp. has validated improvements in plant growth parameters through its capability to phosphorous solubilization and indole-3-acetic acid production (IAA) (Abdallah et al., 2016). The phosphate solubilizing bacteria (PSB) deliver no longer just phosphate but also vital hint elements, inclusive of iron and zinc, which notably sell plant growth. Additionally, these microorganisms produce enzymes which might be effective in eliminating pathogens, thereby safeguarding plant towards many illnesses (Anand et al., 2016).

Phosphate Mobilizers: Microorganisms that facilitate phosphate mobilization are capable of converting less accessible forms of phosphorus into more available forms (Suther et al*.,*2017). These microorganisms are advantageous bacterium that proficiently facilitate mobilization of phosphorus that dissolves and phosphorus mineralization in organic compounds, both of which represent forms of phosphorus that are not readily available. Notable examples of phosphorus-mobilizing microorganisms (PMB) include *Bacillus*, *Pseudomonas*, and *Rhizobium* (Kirui et al*.,* 2022). Three distinct processes have been identified in relation to this process. The first mechanism involves release of phosphatase enzymes by PMB. The second mechanism pertains to creation of organic acids by PMB. Lastly, PMB may engage in a symbiotic interaction with other fungal mycorrhizae, facilitating the mobilization of soluble phosphorus from areas inaccessible to plant roots through absorption of soluble phosphate via hyphal structures. (Etesami et al*.,* 2021) (Nassal et al*.,* 2018). A significant benefit of *Arbuscular mycorrhiza* lies in its ability to facilitate transport of phosphorus to plants, both organic and inorganic. Notable instances of arbuscular mycorrhizal fungi (AMF) encompass *Entrophospora, Paraglomus sp., Glomus sp., and Acaulospora sp.* In comparison, ectomycorrhizal fungi encompass genera like *Boletus, Laccaria,* and *Amanita* species. Additionally, the fungal endophyte Serendipita has been shown to beautify potassium levels in maize whilst additionally providing protection in opposition to strain because of salinity. (Haro and Benito, 2019).

Plant Growth Promoting Rhizobacteria: Collection of Microorganism that live freely within the rhizosphere, inhabiting the roots of flora and encouraging favorable development effects in flowers is called plant growth promoting rhizobacteria (PGPR) (Beneduz et al*.,*2012). PGPR functions as biofertilizer, encompassing diverse array type bacteria found in soil that inhabit rhizosphere, are associated with rhizoplane on root surface, and exist as endophytes within intercellular spaces (Vandana et al., 2021). Plant growth-promoting bacteria (PGPB) encompass variety of bacteria that exist independently and establish specific symbiotic connections to plants. This category also consists of bacterial endophytes capable of colonizing certain regions of plant tissue, as well as Cyanobacteria (Farrar et al., 2014). Enhancement of plant increase is facilitated by style of mechanisms used by plant boom-selling rhizobacteria (PGPR). These mechanisms encompass nitrogen fixation, mineralization of macro and micronutrients, secretion of exopolysaccharides, the producing of phytohormones, synthesis of siderophores, emission of hydrogen cyanide to inhibit phytopathogen proliferation, and the producing of antibiotics, amongst others (Gouda et al., 2018) (Numan et al., 2018). Plant Growth-Promoting Rhizobacteria (PGPR) encompasses numerous genera, at element of but not limited to Bacillus, Frankia, Pseudomonas, Rhizobium, Micrococcus, Streptomyces, *Xanthomonas*, *Enterobacter*, *Cellulomonas*, *Serratia*, *Arthrobacter*, *Alcaligenes*, *Azotobacter*, *Acinetobacter*, *Actinoplanes*, and *Thiobacillus* (Yadav et al*.,* 2017).

Impact of Biofertilizers on Ecosystems: Despite extensive application of biofertilizers in agriculture over recent decades, there remains a significant lack of detailed information regarding their colonization and ecological dynamics. Furthermore, mechanisms underpinning their relationships with vegetation and resident microorganism's communities continue to intrigue researchers. A critical factor influencing effectiveness of biofertilizers in native environments is indigenous microflora present in rhizosphere. This competitive group, characterized by a wide variety of species, can significantly impact both the survival of biofertilizers and their capacity to encourage plant growth (Hibbing et al*.,* 2010). Moreover, practice of bacterizing seeds and seedlings, as well as implementing soil amendments, can significantly impact structure of indigenous microflora. This impact must be carefully considered in relation to safety of bacterial introduction into environment (Dey et al*.,* 2012). It is essential to carefully consider the non-target effects of microbial biofertilizers, which encompass their impact on organisms on

Table 1. Please provide table caption

Biofertilizers	Mechanism	Groups	Examples	References
Nitrogen fixing	Increase soil nitrogen content by fixing atmospheric N and make it available to the plants	Free-living	*Azotobacter, Anabaena, Clostridium, Aulosira Bejerinkia, Nostoc, Klebsiella, Stigonema, Desulfovibrio, Rhodospirillum, and Rhodopseudomonas,*	Choudhury and Kennedy, 2004
		Symbiotic	*Rhizobium, Frankia, Anabaena azollae, and Trichodesmium*	
		Associative symbiotic	*Azospirillum spp., Herbaspirillum spp., Alcaligenes, Enterobacter, Azoarcus spp. Acetobacter diazotrophicus*	
Phosphorus solubilizing	Solubilize the insoluble forms of P in the soil into soluble forms by secreting organic acids and lowering soil pH to dissolve bound phosphates	Bacteria	*Bacillus circulans, B subtilis, Pseudomonas striata, Penicillium spp. B. polymyxa Micrococcus Agrobacterium, Aereobacter and Flavobacterium*	Board, 2004
		Fungi	*Penicillum spp., Aspergillus awamori and Trichoderma*	
Phosphorus mobilizing	Transfer phosphorus from the soil to the root cortex. These are broad spectrum bio-fertilizers	Mycorrhiza	*Arbuscular mycorrhiza, Glomus spp., Gigaspora spp., Acaulospora spp., Scutellospora spp., and Sclerocystis spp.*	Chang, 2009
Potassium solubilizing	Solubilize potassium (silicates) by producing organic acids that decompose silicates and help in the removal of metal ions and make it available to plants	Bacteria	*Bacillus. mucilaginosus, B., circulanscan, B., edaphicus, and Arthrobacter spp.*	Etesami et al., 2017
		Fungi	*Aspergillus niger.*	
Potassium mobilizing	They mobilize the inaccessible forms of potassium in the soil.	Bacteria	*Bacillus spp.*	Jha, 2017
		Fungi	*Aspergillus niger.*	
Micronutrient	Oxidizing sulfur to sulfates which are usable by plants.	Sulfur oxidizing	*Thiobacillus spp.*	Itelima et al., 2018
	Solubilize the zinc by proton, chelated ligands, acidification, and by oxidoreductive systems.	Zinc solubilizing	*Mycorhiza Pseudomonas spp., and Bacillus spp*	Kamran et al., 2017
Plant growth Promoting	Produce hormones that promote root growth, improve nutrient availability, and improve crop yield	Plant growth Promoting rhizobacteria	*Pseudomonas spp., Agrobacterium, Pseudomonas fluorescens, Arthrobacter, Erwinia, Bacillus, Rhizobium, Enterobacter, Streptomyces, and Xanthomonas*	Backer et al., 2018

organisms beyond intended pathogens, their cycles of biogeochemistry, alterations in texture of soil, and modifications to soil properties such as water retention, porosity, and overall fertility, as well as their role in erosion prevention (Pereg and McMillan 2015). Several studies conducted over extended periods are essential for drawing conclusions regarding efficacy and risk factors associated with bioinoculants. Consequently, it is evident that further comprehensive study is necessary to evaluate long-term effects of biofertilizers on non-target organisms prior to deeming these "safe" bioinoculants for commercial use. Furthermore, the impact of biofertilizers not on target communities has been examined through both culturally dependent and independent methodologies, encompassing both physiological and genetic assessments. While evaluation of microbial community compositions via both cytochemical and plating techniques provides valuable framework for investigating the influence of biofertilizers on resident microorganisms, the integration of advanced technology is imperative for a thorough examination of their effects on soil function and microflora. Although DNA serves as a dependable marker for assessing diversity and potential of community, recent advancements in extraction of messenger RNA (mRNA) from soil present significant opportunity to enhance evaluation of risk and efficiency studies involving biofertilizers. Furthermore, mRNA-based strategy would offer insights into actual biofertilizer functional diversity at a given period points within studied system. Therefore, it is crucial to employ high-throughput methods with greater resolution alongside traditional techniques for a comprehensive analysis of risk assessment, diversity, and efficacy of biofertilizers before to their introduction into ecosystem. (Sharma et al*.,* 2012).

Impact of Biofertilizers on Plants: The relationship between elevated photosynthesis and enhanced plant growth is evident, as nearly 90% of biomass from plants is produced through absorption of CO_2 in photosynthetic process (Long et al*.,* 2006). Application of advantageous microorganisms, specifically endophytes that can synthesize growth hormones like indole-3-acetic acid (IAA) and ACC deaminase, has been shown to enhance potassium absorption in plant tissues while simultaneously reducing ethylene concentrations, thereby contributing to adaptability to stress in different plant species (Chaudhary et al*.,* 2022a). Inoculating plants with biofertilizers such as *Bradyrhizobium sp*. *IRBG* 271, *Rhizobium sp*. *IRBG 74*, and *R. leguminosarum* resulted in notable rise in single-leaf photosynthetic rate in comparison to uninoculated control. IRBG strain, in particular, showed greatest improvement in activity of photosynthetic, with an increase of 14% compare to control group (Peng et al*.,* 2002). Biofertilizers functioning as endophytes demonstrate a range of associations with their host plants, which can be classified as mutualistic, parasitic, or symbiotic. These organisms colonize tissues of plants in a manner that does not lead to disease, ultimately offering advantages to vegetation (Chaudhary et al., 2022b). The endophytes can gain benefits of mutualistic relationships, as they obtain nourishment from their host plants and propagate through transmission of host seeds. Additionally, they facilitate absorption of essential nutrients like nitrogen, magnesium, zinc, and phosphorus from soil, which they subsequently supply to host plant, thereby promoting its growing and overall survival (Bamisile et al*.,* 2018). In previous study was noted that under heat stress, Pseudomonas sp. increased plant growth by promoting production of heat shock proteins (HSPs) and reducing reactive oxygen species (ROS). Additionally, Paenibacillus sp. contributed to the growth of Phaseolus vulgaris by facilitating synthesis of hydrogen cyanide (HCN), siderophores, and indole-3-acetic acid (IAA) in conditions of salinity stress (Gupta and Pandey, 2019). Shukla et al*.,* (2012) Research indicates that application of Trichoderma harzianum to rice plants leads to improved root growth and offers a protective effect against drought stress. Pseudomonas putida inoculation enhanced production of abscisic acid, salicylic acid, and flavonoids thereby providing protection to soybean plants against stress from drought (Kang et al*.,* 2014). Pseudomonas species inoculation has been shown to enhance resilience of maize plants against drought stress, resulting in increased sugar content and biomass in treated specimens. This protective effect is attributed to dehydrin protein upregulation and elevated the proline levels (Sandhya et al*.,* 2010). Gond et al*.,* (2015) Studies have shown that inoculating tropical corn with Pantoea agglomerans under conditions of stress from salt (0-100 mM) significantly enhances both plant growth and tolerance, phenomenon linked to aquaporin supregulation. Similarly, Bacillus megaterium has been found to influence aquaporin gene regulation in maize during salt stress, thereby enhancing root growth and leaf water retention.

Impact of biofertilizers on Heavy metals remediation: Metals constitute natural component of soils, with several of them serving as essential micronutrients for plant development. Nevertheless, ongoing human sports, sizable agricultural practices, and speedy tempo of industrialization have resulted in essential environmental problems added on with the aid of the release of pollution, along with natural contaminants, toxic waste, and heavy metals (Shinwari, et al., 2015). Heavy metals constitute a primary institution of inorganic pollution which are able to dissolving in water and gathering in soil environment, mainly due to their persistent and non-degradable characteristics (Akhtar et al., 2013). Harmful heavy metals found in various states of valence encompass lead (Pb), copper (Cu), nickel (Ni), mercury (Hg), chromium (Cr), cadmium (Cd), zinc (Zn), and arsenic (As). While these metals are crucial micronutrients for flowers, excessive accumulation can be unfavourable to most plant species. Elevated concentrations of heavy metal ions in surroundings are swiftly utilized by plant roots and subsequently transported to shoots and leaves, resulting in stress that disrupts metabolic processes, inhibits growth, and may ultimately lead to plant mortality (Mehes-Smith et al*.,* 2013). Additionally, elevated levels of soil-borne heavy metals diminish fertility of soil and have a detrimental impact on microorganism community (Lenart and Wolny-Koładka, 2013). The remediation heavy metals from soil presents significant challenges because their non-biodegradable nature. Detoxification can only be achieved through alterations in their oxidation state. Generally, heavy metals exhibit greater toxicity in their oxidized forms compared to their reduced counterparts (Wuana and Okieimen, 2011). Various techniques, such as biological, physical, and chemical methods, have been employed to eliminate pollutants from metals. However, bioremediation will be simplest approach for removal because of its price-performance and simplicity of utility, especially while contrasted with physiochemical detoxification technologies, which have a tendency to be high-priced and destructive to soil homes ((Lim et al., 2014). Selection of rhizobacteria that sell plant improvement (PGPR) includes *Achromobacter chroococcum* and *Achromobacter xylosoxidans*, *Bacillus subtilis*, *Bacillus megaterium*, *Bradyrhizobium*, *numerous Pseudomonas species, Brevibacillus species*, *Rhizobium, Sinorhizobium*, *Ralstonia metallidurans, Pseudomonas putida*, *Pseudomonas aeruginosa, Kluyvera ascorbata*, and *Mesorhizobium species*, *Ochrobactrum* and *Variovox paradoxus species, Psychrobacter species,* and *Xanthomonas species*. These microorganisms are integral to bioremediation processes addressing heavy metallic infection (Shinwari et al., 2015). It is well established that presence of heavy metals inside the environment causes pressure in flowers, which sooner or later triggers synthesis of ethylene hormone. Elevated concentrations of this hormone can adversely affect plant boom (Hossain et al*.,* 2012). Among several strategies that plant growth-promoting rhizobacteria (PGPR) employ for plant defense, generation of 1-aminocyclopropane-1-carboxylate (ACC) deaminase is particularly significant, as it helps to reduce the concentration of ethylene, a hormone that induces stress in plants (Singh et al*.,* 2015). By producing ACC deaminase, PGPR offer a vital line of defense for host plants, helping them to address stress responses that arise from toxicity of heavy metal. Moreover, PGPR further mitigate metal toxicity through generation of microbial siderophores (Radzki et al*.,* 2013). PGPR can aid in diminishing metal toxicity by utilizing biosorption mechanisms, which involve binding of heavy metals to microbial cells. This process can occur through both metabolically dependent and independent pathways (Dary et al*.,* 2010).

Impact of Biofertilizers on Pesticide Remediation: Nematicides, herbicides, fungicides, and insecticides are employed to manage or suppress diseases of plants. Application of pesticides is vital for contemporary agricultural methods, serves as vital tool for effective pest management. Nonetheless, overuse and prolonged application of these chemicals can have detrimental impacts on environment and present serious hazards to human health and plant life, as they can infiltrate tissues of living organisms, leading in relation to bioaccumulation (Kumar and Puri, 2012) (Aktar et al*.,* 2009). Bioremediation practices for remediation of pesticide pollutants have emerged as a subject of considerable interest, attributed to their environmentally sustainable method, fee-effectiveness, and efficacy in disposing of pollutants from ecosystems (Nawaz et al., 2011). Currently, examine of bacterial traces which can degrade pesticides is rising as a promising avenue for addressing poor outcomes related to pesticide use. Numerous examine has been performed on plant growth-selling rhizobacteria (PGPR), highlighting their good-sized roles in horticulture, forestry, agriculture, and environmental sustainability. As an end result, capacity of PGPR in the bioremediation of pesticides has been very well investigated (Shaheen and Sundari 2013). This has been observed that certain microbes., including *Gordonia, Klebsiella, Paenibacillus, Pseudomonas, Serratia, Bacillus, Enterobacter, Azospirillum,* and *Azotobacter*, are able to diminishing toxicity of pesticide (Shaheen and Sundari, 2013). Beyond these strains, *Actinomycetes* exhibit noteworthy potential for biodegradation and biotransformation of pesticide compounds. Microbes are primarily utilizing enzymatic degradation as main mechanism for pesticide degradation. This process encompasses three significant enzyme systems: Esterases, mixed function oxidases (MFO), and hydrolases during initial stage of metabolic, followed by glutathione S-transferases (GST) system in later stage (Ortiz-Hernández et al*.,* 2013). Moreover, this has been observed several enzymes that catalyze an extensive range of reactions, variety of processes, such as oxidation and hydrolysis, inclusion of amino groups to nitro groups, dehalogenation, transformation of nitro groups into amino groups, ring cleavage and substitution of oxygen for sulfur, and the metabolism of side chains, which have been found to alleviate toxicity posed by pesticides (Ramakrishnan et al*.,* 2011). The analysis of multiple reports suggests that Plant Growth-Promoting Rhizobacteria (PGPR) use offers a promising method for decreasing pesticide residues in soil in an environmentally sustainable manner.

Impact of Biofertilizers on Parasitic Nematodes in Crops: El-Haddad et al*.,* (2011) demonstrated that various biofertilizers made of bacteria, specifically nitrogen-fixing bacteria such as four strains of Paenibacillus polymyxa, phosphate-solubilizing bacteria like Three strains of B. megaterium and potassium solubilize bacteria including Three strains of Bacillus circulans were individually applied to plants of tomato affected by root-knot nematode M. incognita in potted sandy soil. The study revealed that all biofertilizers made of microorganisms exhibited notable nematicidal properties, with B. circulans KSB2, B. megaterium PSB2, and P. polymyxa NFB7 showing most significant reduction of nematode populations compared to the control group that was not inoculated. Furthermore, Application of these biofertilizers resulted in enhanced length of shoot (cm), an increased number of leaves on per plant, as well as greater dry weight of shoot (g) and dry weight of root (g) in tomato plants, in contrast to those affected by nematodes that did not receive biofertilizer inoculation. Khan et al*.,* (2012) demonstrated that Chilli (*Capsicum annuum* L.) plant growth, yield, and quality affected by nematode infestation were significantly enhanced through inoculation with biological nitrogen-fixing agents, specifically *Azotobacte*r and *Azospirillum*. Ismail and Hasabo (2000) investigated effectiveness of six new commercial biofertilizers from Egypt, including *blue-green algae*, *phosphorine*, *serealin*, *nitrobien*, *rizobacterin*, and *microbien*, in combating M. *incognita* in the sunflower cultivar Giza 101. All biofertilizers that were tested demonstrated a significant decline in nematode populations. The most effective treatment in suppressing these populations was rizobacterin, with phosphorine and nitrobien following closely behind. It has been documented that bacteria similar to biofertilizers commonly release a range of compounds, including alcohol, hormones, phenolic chemicals, fatty acids, hydrogen sulfide, enzymes, and volatile compounds, which play a role in curbing the development of plant-parasitic nematodes (Youssef and Eissa, 2014). These products might exhibit hazardous effects on nematodes, or they could indirectly change rhizosphere environment, which may contribute to a reduction in population of nematode (Youssef and Eissa, 2014).

Impact of Biofertilizers on Degraded Land Soil Reclamation: The process of Exploiting mineral resources in considerable degradation of soil, modifies microorganism’s communities, and adversely affects vegetation, culminating in destruction of extensive land areas. The gradual proliferation of these altered landscapes threatens productivity of agriculture and forests while also upsetting natural equilibrium of ecosystem. This has been constantly cited that in different mining operations, vitamins are leached away due to heightened rate of erosion, which in end undermines soil productiveness (Sheoran, et al.,2010). A sort of useful microbes regularly implemented in agricultural practices encompasses species inclusive of *Streptomyces*, *Pseudomonas*, *Bacillus*, *Azospirillum*, *Mycorrhizae, Rhizobia*, and *Trichoderma*. These microorganisms play an important characteristic in decomposition of organic remember in the soil, thereby improving the delivery of critical macronutrients, in conjunction with Calcium, magnesium, sulfur, potassium, phosphorus, and nitrogen, further to micronutrients which includes Zinc, manganese, molybdenum, iron, copper, chlorine, and boron for crop flora (Imran et al., 2015). It has been documented that biofertilizers considerably make a contribution to soil fertility, decorate crop productivity, and improve profitability. Beneficial microorganisms are critical for breakdown of natural materials within soil, thereby growing availability of vital macronutrients inclusive of calcium, magnesium, sulfur, potassium, phosphorus, and nitrogen, at the side of micronutrients along with zinc, manganese, molybdenum, iron, copper, chlorine, and boron for crop plant life (Adhikari, et al., 2001). In a nation of vulnerability, reclamation serves because system that reinstates ecological integrity of regions affected by mining activities. The effective reclamation of mine spoil dumps depends on establishment of a thriving indigenous microbial community, which plays a vital role in forming soil structures that facilitate growth of plant and in generating essential plant nutrients through various biogeochemical cycles (Kumar et al*.,* 2013). The procedure of reclaiming a location for mining presents significant challenges, as these locations not only experience a decline in fertility and productivity but also lose their capacity to sustain Plant and microbial communities (Chaubey and Prakash 2014). Biofertilizers are applied to enhance soil fertility through the processes of atmospheric Phosphate solubilization and nitrogen fixation, and creation of substances that encourage development of plants (Marschner, 1995). Maintenance of ecosystem balance and productivity is significantly influenced by various factors. The restoration of degraded land ecosystems can be partially achieved through the implementation of tree plantations and use of organic amendments, which increase soil fertility and productivity. Mining activities lead to severe acidification of soils at mining sites, adversely impacting plant growth. The introduction of organic amendments can elevate the pH levels of these soils, thereby improving not only the pH but also overall water-retention capacity, quality of soil, and facilitating a gradual release of nutrients (Diacono and Montemurro 2010). Application of bioinoculants plays significant role in mitigating detrimental effects of soil salinity by enhancing physicochemical characteristics of soil, which in turn leads to increased agricultural yield (Jiménez-Mejía et al*.,* 2022). Consequently, one can assert that upkeep of effective soil reclamation depends on presence of leguminous plants in the plant community and healthy operation of microbial community in areas affected by mining. It has been observed that integration of three bacterial biofertilizers- *Pseudomonas*, *Bacillus lentus*, and *Azospirillum brasilense* leads to an increase in antioxidant enzyme expression and chlorophyll content in leaves experiencing stress, which in turn fosters the establishment of a more advanced photosynthetic system within plant (Heidari and Golpayegani 2012). Application of biofertilizers is instrumental in improving soil quality through provision of nutrients and establishment of a natural environment in the rhizosphere. This practice helps mitigate nutrient leaching and overspill, while also facilitating effective crop residue management. Furthermore, the use of microbial inoculants can lead to a decrease in quantity of chemical fertilizers required and enhance the efficiency of those that are utilized (Puneet, et al*.,* 2012).

Emerging Perspectives on Biofertilizers: The incorporation of diverse biofertilizers into agricultural practices represents burgeoning area of research and application in contemporary agriculture. Certain bacterial strains are currently being utilized effectively in several developing nations, and their adoption is anticipated to increase over time (Weekley, et al*.,* 2012). A significant proportion of biofertilizers produced exhibit effectiveness tailored to particular crops, soil types, and environmental conditions. Plant growth and development are affected by various biotic and abiotic factors within soil ecosystem (Bramhachari, et al*.,*2018). Biofertilizer's prospects in agriculture presents significant opportunities for transformative change. These environmentally friendly alternatives, which utilize beneficial microorganisms, are set to play a crucial role in tackling urgent worldwide concerns like environmental sustainability, mitigation of climate change, and reduction of dependence on expensive and harmful agricultural inputs. The establishment of strong regulatory frameworks and standards, along with broad acceptance and adoption by farmers and stakeholders, will be essential for effective integration of biofertilizers into conventional agricultural practices. With ongoing innovation, collaboration, and investment, biofertilizers are likely to become a fundamental component of improving food security, encouraging environmental care, and fostering sustainable agriculture, and strengthening resilience of farming communities globally (Kumar, et al*.,* 2024).

2. CONCLUSION

Biofertilizers gift a promising opportunity to chemical fertilizers in improving soil fertility and crop yield, aligning with worldwide shift closer to sustainable agricultural practices. The assessment highlights that biofertilizers, like as nitrogen-solving bacteria, phosphorus-solubilizing microbes, and Mycorrhizal fungus, provide severa environmental and monetary benefits. They enhance soil health with the resource of way of enriching microbial range, enhancing nutrient availability, and decreasing the reliance on artificial fertilizers, that might have detrimental consequences on each surroundings and health of human.

Integrating biofertilizers in systems of agriculture now not best will increase crop productiveness however additionally contributes to the reduction of soil erosion, water contamination, and greenhouse fuel emissions, making them quintessential thing of sustainable farming. Additionally, biofertilizers support soil organic content, leading to long-time period improvements in soil structure and fertility, which might be critical for keeping agricultural productiveness over years.

However, the huge adoption of biofertilizers faces demanding situations including lack of knowledge, inconsistent product high-quality, and limited studies on their effectiveness below numerous environmental conditions. Despite those demanding situations, advancements in biotechnology, alongside authorities support and farmer schooling, are step by step paving the way for biofertilizers to turn out to be a mainstream solution in sustainable agriculture.

Overall, biofertilizers maintain terrific ability in addressing the twin assignment of improving agricultural productiveness whilst retaining and restoring soil fitness. As the world movements in the direction of more sustainable farming practices, biofertilizers will play a significant component in ensuring meals safety, protecting surroundings resources.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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