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Biofertilizer: A sustainable solutions for soil fertility and environmental harmony

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Abstract
This review explores through the topic of biofertilizers and examines their value in boosting soil fertility and encouraging plant growth. Chemical fertilizers, which frequently have negative effects on the ecosystem, can be replaced with biofertilizers, which are made from living organisms. Biofertilizers supply necessary elements like nitrogen, phosphorus, and potassium, facilitating nutrient uptake by plants. They do this by utilizing atmospheric nitrogen fixation and nutrient release from the soil. These bio-based solutions also promote the growth of advantageous microorganisms, which enhances soil health, structure, and water-retentive properties. Biofertilizers hold great promise in addressing the difficulties of feeding a growing global population while mitigating environmental effects. They are embraced by organic farming, sustainable agriculture, and regenerative farming practices.

Keywords: *Biofertilizers, soil fertility, plant growth, organic farming, regenerative, agriculture*.

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I. INTRODUCTION

In pursuit of enhancing soil fertility and promoting sustainable agricultural practices, the utilization of biofertilizers and microbial inoculants has gained significant attention. These bio-based solutions aim to optimize the quantity and biological/metabolic activity of beneficial microorganisms, thereby accelerating microbial processes and increasing the availability of essential nutrients in usable forms for plants. In contrast to chemical fertilizers, which have contributed to agricultural productivity and yields, their repetitive application has led to adverse effects on soil fertility, structure, and environmental well-being. Recognizing the economic and environmental advantages of organic fertilizers, the use of biofertilizers emerges as a sensible choice for nourishing the earth and ensuring long-term sustainability [1].

Biofertilizers encompass a range of microbial agents that collaborate with plants, making essential nutrients more accessible for uptake. Symbiotic nitrogen-fixing organisms like Rhizobium spp. and non-symbiotic free-living nitrogen fixers such as Acetobacter and Azospirillum represent just a few examples of biofertilizers. Additionally, microbial inoculants consisting of Anabaena, Bacillus, Pseudomonas, and Penicillium strains that solubilize phosphate, as well as organic fertilizers enriched with cellulolytic microorganisms, contribute to this diverse arsenal [2]. These biofertilizers play a crucial role in addressing the primary macronutrient requirements for plant growth and development, including nitrogen, potassium, and phosphate. Although soils naturally contain these nutrients in insoluble forms, making them less accessible to plants, biofertilizers help convert them into usable forms, facilitating nutrient absorption [3].

India, being predominantly an agricultural nation with its economy and over 50% of its population dependent on agricultural products, faces the challenge of balancing productivity with sustainability. Traditional practices of mineral extraction and widespread application of chemical fertilizers have proven to be environmentally detrimental, economically unsustainable, and detrimental to soil fertility. Recognizing these limitations, organic fertilizers, including biofertilizers, emerge as a viable alternative that can improve soil health, productivity, and long-term sustainability [3].

In light of these considerations, this review aims to explore the potential of biofertilizers as sustainable solutions for enhancing soil fertility and agricultural productivity. By investigating their mechanisms, benefits, and applications, we can gain valuable insights into how biofertilizers can contribute to the goals of sustainable agriculture, environmental harmony, and food security.

II. BIOFERTILIZERS: MAXIMIZING SOIL NUTRIENT DYNAMICS

Microorganisms play a crucial role in orchestrating a multitude of biochemical changes within the soil, profoundly influencing nutrient dynamics. These changes encompass the mineralization of organically bound nutrients, exchange reactions, atmospheric nitrogen fixation, and various other modifications that augment the availability of nutrient-rich soil facilitated by biofertilizers. Notably, the majority (72%) of nitrogen enrichment on the Earth's surface is attributed to biological nitrogen fixation, a process carried out by a group of microorganisms. These microorganisms possess the remarkable ability to produce the nitrogenase enzyme, which catalyzes the transformation of inert N_2 into NH_3, a form readily assimilated by plants. *Rhizobium*, *Azotobacter*, *Azospirillum*, and Blue-Green Algae exemplify common beneficial organisms involved in nitrogen fixation. Additionally, certain microorganisms exhibit the capacity to dissolve insoluble soil phosphorus, while others utilize elongated filaments to transport accessible phosphorous from distant locations that plant root hairs cannot reach. An example of such a beneficial organism is Vesicular Arbuscular Mycorrhiza (VAM). Although only a small percentage of heterotrophic organisms possess the capability to rapidly degrade cellulose, these invaluable microorganisms are harnessed and cultivated in suitable carriers. When introduced into the soil, they significantly enhance crop growth and yield. Collectively referred to as biofertilizers, bioinoculants, microbial inoculants, or microbial fertilizers, these microorganisms used as carriers demonstrate immense potential in sustainable agriculture and soil fertility enhancement [3,4].

III. BENEFICIAL MICROBES IN AGRICULTURE

3.1 *Azospirillum*

It is highly valued as a diazotrophic bacterium due to its mutually beneficial symbiotic relationship with the roots of graminaceous plants. Specifically, it plays a crucial role in promoting the growth of leguminous crops. The suitability of legumes for *Azospirillum* colonization is attributed to their microaerophilic nature, with some strains even capable of aerobic activity, and their classification as gram-negative bacteria. This bacterium was initially identified by Beijerinck, who named it *Spirillum lipoferum* before renaming it *Azospirillum*. Notably, *Azospirillum* exhibits the ability to fix nitrogen, converting atmospheric nitrogen into biologically useful forms such as ammonia. Furthermore, it produces compounds like indole acetic acid, which actively contribute to the developmental processes of plants [5].

3.2 *Rhizobium*

Plant growth-promoting *Rhizobacteria* (PGPR) form a diverse group of microbes recognized for their ability to enhance plant growth. They achieve this by colonizing the rhizosphere, the region surrounding plant roots, where they act as biocontrol agents and produce plant hormones. PGPR have the remarkable capability to modify physiological processes in plants, leading to increased nutrient uptake. One of the notable contributions of PGPR is their production of siderophores, a group of iron transport molecules with high affinity. These siderophores not only facilitate the transport of iron to plants but also serve as growth-promoting agents, further enhancing plant development [6].

3.3 *Rhizobium*

Azotobacter, initially identified by Beijerinck, is a gram-negative bacterium that exists freely in the rhizosphere soil of various plant species. This versatile bacterium is well-known for its ability to fix atmospheric nitrogen in its natural habitat, making it a valuable diazotroph. In agriculture, *Azotobacter* is commercially employed for multiple crops and is commonly recognized by the brand name Azotobacter due to its flexibility and nitrogen-fixing capacity. Some species of *Azotobacter* have the unique capability of producing alginic acid, a substance widely used in the medical and culinary industries as an additive in ice creams and cakes. Apart from nitrogen fixation, *Azotobacter* also synthesizes a range of phytohormones, including auxins, which contribute to plant growth and development. Additionally, *Azotobacter* plays a significant role in releasing heavy metals from the soil, making it beneficial for bioremediation purposes [7].

3.4 *Cyanobacteria*

Cyanobacteria, also known as blue-green algae, hold significant potential for addressing the global challenges associated with population growth and the need for safe and nutritious food. With the world's population projected to reach 9.7 billion within the next 30 years, India is expected to contribute the largest share. The demand for healthy and uncontaminated food directly influences population growth, and by 2029, the World Health Organization anticipates a 50% increase in food production. To enhance agricultural output while mitigating the environmental and human health risks posed by chemical fertilizers, researchers have turned to "green technology" that leverages the use of bacteria to create eco-friendly ecosystems. *Cyanobacteria*, in particular, offer several applications within green technology to boost crop yield and soil fertility. They possess the unique ability to break down various substances. As a newly discovered microorganism in sustainable agriculture, cyanobacteria, specifically diazotrophs, play a vital role in producing affordable and environmentally friendly biofertilizers. These diazotrophs help address plant nitrogen deficiencies, improve soil aeration, enhance water retention, and even supply vitamin B12. In the cultivation of rice crops, nitrogen-fixing cyanobacteria such as *Nostoc linkia, Anabaena variabilis, Aulosira fertilisima, Calothrix* sp., *Tolypothrix* sp., and *Scytonema* sp. are particularly effective. Anabaena and Nostoc, found on the soil and rock surfaces, have the capacity to fix 20-25 kg/ha of atmospheric nitrogen, with Anabaena capable of fixing up to 60 kg/ha/season while enriching soils with organic matter [12][13]. The theoretical applications of cyanobacteria in environmentally and agriculturally sustainable practices continue to showcase their potential in shaping a more sustainable future.

3.5 *Azolla*

Azolla, with its nitrogen-rich composition of 4-5% on a dry basis and 0.2-0.4% on a wet basis, holds significant potential as an organic manure and nitrogen source for rice cultivation [14]. The utilization of *Azolla* as a biofertilizer offers a key advantage in its rapid decomposition in the soil, providing rice plants with a readily available nitrogen source. Furthermore, *Azolla* enhances the availability of essential micronutrients such as phosphorus, potassium, zinc, iron, molybdenum, and others [15]. Prior to rice cultivation, *Azolla* can be incorporated into the fields as a green biofertilizer. In India, the most popular species is Azolla pinnata, which is economically viable through vegetative propagation methods. Additionally, several other *Azolla* species, including *Azolla caroliniana, Azolla microphylla, Azolla filiculoides,* and *Azolla mexicana,* have been introduced to India due to their remarkable biomass production capabilities [16]. The utilization of *Azolla* as a biofertilizer presents a promising approach to enhance the nutrient content of soils and support sustainable rice farming practices.

3.6 *VAM (vesicular-arbuscular mycorrhiza)*

Mycorrhiza is the result of a symbiotic relationship between a plant root and a fungus. Specifically, angiosperm roots and certain phycomycetous fungi form a mutualistic association known as vesicular-arbuscular mycorrhiza (VAM) [17]. As the fungus colonizes the root cortex, it forms a mycelial network along with unique structures called vesicles (bladder-like structures) and arbuscules (branched finger-like hyphae). The mycelia, whether aseptate or septate, spread intercellularly, causing minimal damage to the plant tissue. Among these structures, the arbuscules are particularly distinctive as they are generated intracellularly and likely play a role in nutrient absorption [18]. On the other hand, the vesicles serve as storage compartments and can be found both inter- and intracellularly. The mycorrhizal relationships are mainly formed by six genera of *Endogonaceae* fungi, including *Glomus*, *Gigaspora*, *Acaulospora*, *Entrophospora*, *Sclerocystis,* and *Scutellospora*, which are often identified by the unique spores they produce [19,20,21]. The establishment of mycorrhizal associations contributes to the improved nutrient uptake and overall growth of plants, highlighting the significance of this symbiotic relationship in the plant kingdom.

IV. ROOT-MICROBE INTERACTION

The composition of soil-dwelling organisms, particularly those in close proximity to plants, is heavily influenced by the types of plants present [22]. Consequently, these soil organisms play a significant role in the growth and functioning of plants [23]. Microorganisms establish symbiotic relationships with plants by releasing various beneficial substances into the rhizosphere, which are then absorbed by plants. These substances facilitate the control of plant transcriptome and include cytokinins, auxins, and gibberellins secreted by the microbial community residing near plant roots [24]. The selection of rhizospheric microbial populations is carefully guided by plant-specific root exudates. For example, beans release citric acid from their roots, impacting the plant's physiology, while fumaric acid from banana roots attracts *Bacillus amyloliquefaciens* and triggers biofilm formation, attracting Bacillus subtilis [25]. Moreover, other substances like tryptophan found in root exudates are utilized by bacteria in the biosynthesis of indole acetic acid (IAA), which is crucial for the activities of plant growth-promoting rhizobacteria (PGPR) [26]. Furthermore, plant roots exude aminocyclopropane-1-carboxylic acid (ACC), which serves as a precursor for ethylene (ET), a stress hormone. It also acts as a carbon and nitrogen source for bacterial growth. Microbes residing in the roots and involved in root exudate assimilation express the acdS gene, which enables the utilization of ACC. This process helps maintain a balance between the ACC levels inside and outside the plants, with ACC deaminase-producing PGPRs playing a key role [27][28].

V. MICROBES WIDELY USED IN BIOFERTILIZER PREPARATION

Microbes used in the preparation of biofertilizers are primarily involved in three key mechanisms. Firstly, they contribute to nitrogen fixation by converting atmospheric nitrogen into a usable form for plants. Secondly, these microbes play a role in phosphate solubilization, making insoluble forms of phosphate available to plants. Lastly, they enhance the availability of potassium through processes such as organic acid production, chelation, and ion exchange. These mechanisms help improve nutrient availability and promote sustainable agricultural practices which are further discussed.

5.1 *Nitrogen fixation*

The mechanism called nitrogen fixation, which involves free-living organisms converting atmospheric nitrogen (N_2) into a more usable form for plants and other organisms. Nitrogen is essential for the growth and development of living organisms, but atmospheric nitrogen is generally in an inert form that cannot be directly utilized by most organisms. Nitrogen fixation is the process by which certain microorganisms, known as diazotrophs, carry out this conversion. Diazotrophs possess a specialized enzyme called nitrogenase, which plays a crucial role in nitrogen fixation. Nitrogenase has the ability to break the strong triple bond between nitrogen (N_2) molecules, transforming them into a more reactive form. This process requires a considerable amount of energy and is highly sensitive to oxygen. Therefore, diazotrophs have evolved mechanisms to protect nitrogenase from oxygen, either by living in anaerobic environments or by producing specialized structures, such as heterocysts in cyanobacteria, that create a low-oxygen environment. When nitrogenase enzyme is active, it catalyzes the conversion of atmospheric nitrogen (N_2) into ammonia (NH_3) through a series of complex reactions. These reactions involve the addition of hydrogen atoms to the nitrogen molecule, resulting in the formation of ammonia. Ammonia is a form of nitrogen that can be easily assimilated by plants and other organisms. It serves as a crucial building block for the synthesis of amino acids, proteins, and other nitrogen-containing compounds necessary for various biological processes. The availability of fixed nitrogen through nitrogen fixation is vital for the growth and productivity of plants, as they require nitrogen to synthesize essential biomolecules. In natural ecosystems, nitrogen-fixing bacteria and archaea contribute significantly to the overall nitrogen budget by converting atmospheric nitrogen into ammonia, making it accessible to plants and other organisms. This process plays a crucial role in maintaining nitrogen cycling and the overall fertility of the soil [29,45]. *Azospirillum spp., Enterobacter, Anabaena, Azolla spp., Rhizobium spp.* are well known to perform nitrogen fixation.

In summary, free-living organisms capable of nitrogen fixation produce the nitrogenase enzyme, which converts inert atmospheric nitrogen (N_2) into ammonia (NH_3). This ammonia serves as a valuable source of nitrogen for plants, enabling them to fulfill their nutritional requirements and support their growth and development.

5.2 *Phosphate solubilization*

Certain microorganisms, such as *Arthrobacter* spp., *Penicillium* spp., *Aspergillus niger*, and *Aspergillus awamori*, have the ability to release organic acids into the soil. These organic acids can influence the pH of the soil and also play a role in the solubilization of insoluble forms of phosphate, making them available for plant uptake. The organic acids produced by these microorganisms, such as citric acid, oxalic acid, and gluconic acid, have the capacity to lower the pH of the surrounding soil. This acidification occurs because these organic acids release hydrogen ions (H+) when they dissociate in water, thus increasing the concentration of H+ ions in the soil solution. As a result, the pH of the soil decreases, becoming more acidic. The acidification of the soil has several effects, one of which is the transformation of insoluble forms of phosphate into soluble ones. In many soils, phosphate is present in insoluble forms, bound to minerals or organic matter, which makes it inaccessible to plants. However, the organic acids released by these microorganisms can chelate or bind to the mineral-bound phosphate, forming soluble complexes. This process is known as chelation or complexation.

When the phosphate is in a soluble form, it is readily available for plant uptake. Plant roots can absorb the soluble phosphate and utilize it for various physiological processes, such as energy transfer, nucleic acid synthesis, and cell division. Therefore, the action of these microorganisms in solubilizing bound phosphate enhances the availability of this essential nutrient to plants, promoting their growth and development. It's worth noting that the specific mechanisms of phosphate solubilization can vary among different microorganisms. Some microorganisms produce organic acids that directly dissolve the mineral-bound phosphate, while others may release enzymes that break down organic compounds in the soil, leading to the release of phosphate. Additionally, the effectiveness of phosphate solubilization can depend on factors such as soil pH, temperature, moisture, and the availability of other nutrients [30, 45].

5.3 *Potassium solubilization*

Potassium plays a crucial role in two key processes: removing metals and breaking down silicates, ultimately making silicate ions soluble for plant uptake. It competes with metals for binding sites in the soil, preventing their excessive accumulation and maintaining nutrient balance. Additionally, potassium contributes to the breakdown of insoluble silicates, promoting their weathering into smaller particles. This releases soluble silicate ions that plants can absorb through their roots. Microorganisms like Bacillus species facilitate the transformation of insoluble potassium into a soluble form. They employ enzymes and metabolic pathways to release potassium from its bound forms, enhancing its availability in the soil. These microorganisms also produce organic acids, enzymes, and siderophores that aid in solubilizing potassium compounds, thereby supporting plant nutrition and growth [31,32,46].

Table 1 summarizes the microbes that cause potassium solubilization, phosphorus solubilization, and nitrogen fixation along with their respective mechanisms.

Table 1. Overview of beneficial microbial activities supporting plant growth

Activity	Mechanism	Example of microbe	References
Nitrogen fixation	As a result of free-living organisms fixing atmospheric nitrogen, the nitrogenase enzyme is produced, which converts inert N_2 into NH_3 that is beneficial to plants.	*Azospirillum spp., Enterobacter, Anabaena, Azolla spp., Rhizobium spp.*	[29,45]
Phosphorus solubilization	In order to dissolve bound phosphate, they release organic acid, which lowers soil pH and converts the insoluble forms of phosphate in the soil to soluble ones.	*Arthrobacter spp., Penicillium spp., Aspergillus niger, Aspergillus awamori*	[30,45]
Potassium solubilization	Through organic acid production, ion exchange, siderophore activity, acidification, enzymatic processes, and root-microbe interactions, microbes contribute to the mobilization and availability of potassium, supporting plant growth, and development.	*Bacillus spp.*	[31,32,46]

The activity of the microbes that support plant growth along with the mechanism involved and example is shown in table 2.

Table 2. microbial activity aimed at promoting plant growth

Name of the activity	Mechanism	Example	References
Indole acetic acid (IAA)	Tryptophan can be hydrolysed and deaminated by bacteria that express the tryptophanase enzyme. Tryptophan is reductively deaminated to indole using the intermediary molecule indole pyruvic acid. Tryptophanase catalyses the deamination reaction, which removes the amine ($-NH_2$) group from the tryptophan molecule. In addition to energy, pyruvic acid, ammonium (NH^{4+}), and indole are the reaction's final by-products. Pyridoxal phosphate is required as a coenzyme.	*Rhizobium spp*	[33,47]
Organic acid	Microbes that aid in the growth of plants use a pathway for the production of organic acids. They get their carbon sources from the environment, which are simple organic compounds. These microbes transform the carbon sources into organic acids like citric acid, oxalic acid, malic acid, and gluconic acid through enzymatic reactions. The rhizosphere is where these organic acids are then released and play crucial roles. They help to solubilize minerals like phosphate and potassium, increasing their accessibility for plant uptake, and they chelate essential nutrients like iron, improving their availability to plants. Overall, the rhizosphere's microbes' production and release of organic acids promote plant growth and development.	*Rhizobium spp*	[34,35,48]
Catalase activity	The catalase enzyme produced by certain bacteria contributes to plant growth promotion by detoxifying reactive oxygen species, protecting against pathogens, enhancing nutrient uptake, and inducing systemic resistance. These activities help improve plant health and productivity.	*Staphylococcus spp*	[36,37,49]
Hydrogen cyanide (HCN) production	Our theory is supported by in vitro findings that demonstrate how hydrogen cyanide (HCN) can enhance mineral mobilization and phosphate release when used in conjunction with KCN and mineral sand. One of the primary benefits of HCN is its ability to indirectly increase nutrient availability by sequestering metals in various environments, such as gotrophic alpine habitats. This sequestration process promotes the release of bound nutrients, leading to improved nutrient availability for plant uptake and growth.	*Pseudomonas fluorescens*	[38,50]

VI. BENEFITS OF BIOFERTILIZER

- Biofertilizers improve soil qualities and enable cultivation on dry regions [42].
- The bacteria *Rhizobium*, *Azotobacter*, and *Azospirillum* are effective at reducing soil nitrogen [43].
- *Cyanobacteria* release useful nutrients that encourage the accumulation of organic matter and stabilize nitrogen in the soil [43].
- Increased root surface area, phosphate uptake, water absorption, and mineral absorption are all benefits of mycorrhiza bio-fertilizers, particularly VAM (Vesicular Arbuscular Mycorrhiza) [44].
- The prevalence of harmful bacteria and fungi in the soil is reduced by the presence of VAM [44].
- Bio-fertilizers, which are made from natural resources, have little impact on air pollution and are friendly to the environment [44].
- Certain bio-fertilizers containing *Azotobacter* secrete particular organic substances, providing additional advantages to plant growth [45].

The following microbes are widely used in biofertilizers:
Pseudomonas gessardi, *Pseudomonas fluorescens*, *Pseudomonas azotoformans* [52]
Erwinia aphidicola, *Erwinia amylovora*, *Erwinia persicina*, *Erwinia* spp. [53]
Chrysebacterium arthrosphaerae, *Chrysebacterium gleum*, *Chrysebacterium cucumeris* [54]
Rhizobium spp. [55]
Azotobacter spp. [56]
Azospirillum spp. [57]

VII. CONCLUSION

A promising method for increasing soil fertility and fostering sustainable agriculture is the use of biofertilizers. They are made up of various microorganisms that cooperate with plants to increase nutrient accessibility. The needs of plants for macronutrients are met by biofertilizers like nitrogen-fixing organisms, phosphate-solubilizing microorganisms, and phosphorus solubalizing microorganisms, which additionally enhance nutrient absorption.

REFERENCES

[1]. Farnia, A., & Hassanpour, K. (2015). Comparison between the effect of chemical and biological fertilizers on yield and yield components of wheat (Triticum aestivum L.) Pishtaz cultivar. Indian Journal of Natural Sciences, 5, 7792-7808.
[2]. Al Abboud, M. A., Ghany, T. A., & Alawlaqi,
[3]. M. M. (2014). Role of biofertilizers in agriculture: a brief review. Mycopath, 11 (2) Carvajal-Muñoz, J. S., & Carmona-Garcia, C. E. (2012). Benefits and limitations of biofertilization in agricultural
[4]. practices. Livestock Research for Rural Development, 24(3), 1-8.
[5]. Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB):: Mechanisms, promotion of plant growth, and prospects A review. Journal of soil science and plant nutrition, 17(4), 897-911.
[6]. Yasuor, H., Ben-Gal, A., Yermiyahu, U., Beit-Yannai, E., & Cohen, S. (2013). Nitrogen management of greenhouse pepper production: Agronomic, nutritional, and environmental
[7]. implications. HortScience, 48(10), 1241-1249.
[8]. Suhameena, B., Devi, S., Gowri, R., & Kumar, A. (2020). Utilization of Azospirillum as a Biofertilizer–an overview. Int J Pharm Sci Rev Res, 62(22), 141-145.
[9]. Suhameena, B., Devi, S., Gowri, R., & Kumar, A. (2020). Utilization of Azospirillum as a Biofertilizer–an overview. Int J Pharm Sci Rev Res, 62(22), 141-145.
[10]. Lata, C., & Prasad, M. (2011). Role of DREBs in the regulation of abiotic stress responses in plants. Journal of experimental botany, 62(14), 4731-4748.
[11]. Subramanian, G., & Uma, L. (1996). Cyanobacteria in pollution control. Journal of Scientific and Industrial Research, 55, 685-692.
[12]. Singh, R., Parihar, P., Singh, M., Bajguz, A., Kumar, J., Singh, S., ... & Prasad, S. M. (2017). Uncovering potential applications of cyanobacteria and algal metabolites in biology, agriculture and medicine: current status and future prospects. Frontiers in microbiology, 8, 515.
[13]. Singh, S. P., Pathak, J., & Sinha, R. P. (2017). Cyanobacterial factories for the production of green energy and value-added products: An integrated approach for economic viability. Renewable and Sustainable Energy Reviews, 69, 578-595.
[14]. Hall, D. O., Markov, S. A., Watanabe, Y., & Krishna Rao, K. (1995). The potential applications of cyanobacterial photosynthesis for clean technologies. Photosynthesis research, 46, 159-167.
[15]. Prasad, R. C., & Prasad, B. N. (2001). Cyanobacteria as a source biofertilizer for sustainable agriculture in Nepal. J. Plant Sci. Bot. Orientalis, 1, 127-133.
[16]. Moore, A. W. (1969). Azolla: biology and agronomic significance. The Botanical Review, 35, 17-34.
[17]. Mishra, D., Rajvir, S., Mishra, U., & Kumar, S. S. (2013). Role of bio-fertilizer in organic agriculture: a review. Research Journal of Recent Sciences ISSN, 2277, 2502.
[18]. Al Abboud, M. A., Ghany, T. A., & Alawlaqi, M. M. (2014). Role of biofertilizers in agriculture: a brief review. Mycopath, 11(2).
[19]. Mishra, D., Rajvir, S., Mishra, U., & Kumar, S. S. (2013). Role of bio-fertilizer in organic agriculture: a review. Research Journal of Recent Sciences ISSN, 2277, 2502.
[20]. Allen, M. F., Moore Jr, T. S., & Christensen, M. (1980). Phytohormone changes in Bouteloua gracilis infected by vesicular–arbuscular mycorrhizae: I. Cytokinin increases in the host plant. Canadian Journal of Botany, 58(3), 371-374.
[21]. Bagyaraj, J. Biological interactions with VA mycorrhizal fungi (1984) VA Mycorrhiza. CRC Press, Boca Raton, FL, 131-153.
[22]. Baylis, G. T. S. (1967). Experiments on the ecological significance of phycomycetous mycorrhizas. New phytologist, 66(2), 231-243.
[23]. Crush, J. R. (1974). Plant growth responses to vesicular‐ arbuscular mycorrhiza VII. Growth and modulation of some herbage legumes. New phytologist, 73(4), 743-749.
[24]. Hayman, D. S. (1983). The physiology of vesicular–arbuscular endomycorrhizal symbiosis. canadian Journal of Botany, 61(3), 944-963.
[25]. Kowalchuk, G. A., Buma, D. S., De Boer, W., Klinkhamer, P. G., & Van Veen, J. A. (2002). Effects of above-ground plant species composition and diversity on the diversity of soil-borne microorganisms. Antonie van leeuwenhoek, 81, 509-520.
[26]. Putten, W. H. (2013). van der, Richard D. Bardgett, James D. Bever, T. Martijn Bezemer, Brenda B. Casper, Tadashi Fukami, Paul Kardol, et al, 265-76.
[27]. Fahad, S., Hussain, S., Bano, A., Saud, S., Hassan, S., Shan, D., ... & Huang, J. (2015). Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses: consequences for changing environment. Environmental Science and Pollution Research, 22, 4907-4921.
[28]. Zhang, N., Wang, D., Liu, Y., Li, S., Shen, Q., & Zhang, R. (2014). Effects of different plant root exudates and their organic acid components on chemotaxis, biofilm formation and colonization by beneficial rhizosphere-associated bacterial strains. Plant and soil, 374, 689-700.
[29]. el Zahar Haichar, F., Santaella, C., Heulin, T., & Achouak, W. (2014). Root exudates mediated interactions belowground. Soil Biology and Biochemistry, 77, 69-80.

[30]. Haichar, F. e. Z., Roncato, MA, and Achouak, W. 2012. Stable isotope probing of bacterial community structure and gene expression in the rhizosphere of Arabidopsis thaliana. Fems Microbiology Ecology, 81, 291.
[31]. Glick, B. R., Penrose, D. M., & Li, J. (1998). A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. Journal of theoretical biology, 190(1), 63-68.
[32]. Dursun, A., Ekinci, M., & Dönmez, M. F. (2010). Effects of foliar application of plant growth promoting bacterium on chemical contents, yield and growth of tomato (Lycopersicon esculentum L.) and cucumber(Cucumis sativus L.). Pak J Bot, 42(5), 3349- 3356.
[33]. Aloo, B. N., Mbega, E. R., & Makumba, B. A. (2020). Phosphate-Solubilizing Rhizobacteria: Diversity, Mechanisms, and Prospects in Sustainable Agriculture
[34]. Aloo, B. N., Makumba, B. A., & Mbega, E. R. (2019). The potential of Bacilli rhizobacteria for sustainable crop production and environmental sustainability. Microbiological Research, 219, 26-39.
[35]. Pramanik, P., Goswami, A. J., Ghosh, S., & Kalita, C. (2019). An indigenous strain potassium- solubilizing bacteria Bacillus pseudomycoides enhanced potassium uptake in tea plants by increasing potassium availability in the mica waste- treated soil of North- east India. Journal of applied microbiology, 126(1), 215-222.
[36]. Bric, J. M., Bostock, R. M., & Silverstone, E. (1991). Rapid in situ assay for indoleacetic acid production by bacteria immobilized on a nitrocellulose membrane. Applied and environmental Microbiology, 57(2), 535-538.
[37]. Tsegaye, Z., Gizaw, B., Tefera, G., Feleke, A., Chaniyalew, S., Alemu, T., & Assefa, F. (2019). Isolation and biochemical characterization of Plant Growth Promoting (PGP) bacteria colonizing the rhizosphere of Tef crop during the seedling stage. Journal of Plant Science and Phytopathology, 3(1), 013- 027.
[38]. Trivedi, M. K., Patil, S., & Tallapragada, R. M. (2015). Effect of biofield treatment on the physical and thermal characteristics of aluminium powders. Industrial Engineering & Management, 4(1), 1000151.
[39]. Kumar, A., Kumar, A., Devi, S., Patil, S., Payal, C., & Negi, S. (2012). Isolation, screening and characterization of bacteria from Rhizospheric soils for different plant growth promotion (PGP) activities: an in vitro study. Recent research in science and technology, 4(1), 1-5.
[40]. Castric, P. A. (1975). Hydrogen cyanide, a secondary metabolite of Pseudomonas aeruginosa. Canadian Journal of Microbiology, 21(5), 613-618.
[41]. Singh, R., Pandey, D. K., Kumar, A., & Singh, M. (2017). PGPR isolates from the rhizosphere of vegetable crop Momordica charantia: characterization and application as biofertilizer. Int J Curr Microbiol App Sci, 6(3), 1789-1802
[42]. Raimi, A., Roopnarain, A., & Adeleke, R. (2021). Biofertilizer production in Africa: current status, factors impeding adoption and strategies for success. Scientific African, 11, e00694.
[43]. Prabakaran, S., Mohanraj, T., Arumugam, A., & Sudalai, S. (2022). A state-of-the-art review on the environmental benefits and prospects of Azolla in biofuel, bioremediation and biofertilizer applications. Industrial Crops and Products, 183, 114942.
[44]. Chen, J. H. (2006, October). The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. In International workshop on sustained management of the soil- rhizosphere system for efficient crop production and fertilizer use (Vol. 16, No. 20,pp. 1-11).
[45]. Kalia, A., & Kaur, H. (2019). Nano- biofertilizers: harnessing dual benefits of nano-nutrient and bio-fertilizers for enhanced nutrient use efficiency and sustainable productivity. Nanoscience for sustainable agriculture, 51-73.
[46]. Zahra, Z., Habib, Z., Hyun, H., & Shahzad, H. M. A. (2022). Overview of Recent Developments in the Design, Application, and Impacts of Nanofertilizers in Agriculture. Sustainability, 14(15), 9397.
[47]. Kuila, D., & Ghosh, S. (2022). Aspects, problems, and utilization of Arbuscular Mycorrhizal (AM) application as bio-fertilizer in sustainable agriculture. Current Research in Microbial Sciences, 100107.
[48]. Nosheen, S.; Ajmal, I.; Song, Y. Microbes as biofertilizers, a potential approach for sustainable crop production. Sustainability 2021, 13, 1868.
[49]. Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB):: Mechanisms, promotion of plant growth, and future prospects A review. Journal of soil science and plant nutrition, 17(4), 897-911.
[50]. Jahanian, A., Chaichi, M. R., Rezaei, K., Rezayazdi, K., & Khavazi, K. (2012). The effect of plant growth promoting rhizobacteria (PGPR) on germination and primary growth of artichoke (Cynara scolymus). International Journal of Agriculture and Crop Sciences (IJACS), 4(14), 923-929.
[51]. Ludwig, M. (2016). The roles of organic acids in C4 photosynthesis. Frontiers in plant science, 7, 647. Taylor, W. I., & Achanzar, D. (1972). Catalase test as an aid to the identification of Enterobacteriaceae. Applied microbiology, 24(1), 58-61.
[52]. Rijavec, T., & Lapanje, A. (2016). Hydrogen cyanide in the rhizosphere: not suppressing plant pathogens, but rather regulating availability of phosphate. Frontiers in microbiology, 7, 1785.
[53]. Jahanian, A., Chaichi, M. R., Rezaei, K., Rezayazdi, K., & Khavazi, K. (2012). The effect of plant growth promoting rhizobacteria (PGPR) on germination and primary growth of artichoke (Cynara scolymus). International Journal of Agriculture and Crop Sciences (IJACS), 4(14), 923-929.
[54]. Aryal, S. (2018). Catalase Test-Principles, Uses, Procedure, Result Interpretation with precauti-ons. Available online at https://microbiologyinfo. com/catalase-testprinciple-uses-procedure-result-interpretation-with-precautions. Retrieved 17/05.
[55]. Kumar, A., Maurya, B. R., & Raghuwanshi, R. (2021). The microbial consortium of indigenous rhizobacteria improving plant health, yield and nutrient content in wheat (Triticum aestivum). Journal of Plant Nutrition, 44(13), 1942-1956.
[56]. Kumar, A., Maurya, B. R., Raghuwanshi, R., Meena, V. S., & Tofazzal Islam, M. (2017). Co-inoculation with Enterobacter and Rhizobacteria on yield and nutrient uptake by wheat (Triticum aestivum L.) in the alluvial soil under indo-gangetic plain of India. Journal of plant growth Regulation, 36, 608-617.
[57]. Etesami, H., & Alikhani, H. A. (2016). Co-inoculation with endophytic and rhizosphere bacteria allows reduced application rates of N-fertilizer for rice plant. Rhizosphere, 2, 5-12.