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REVIEW ARTICLE

Integrating microbial consortia into biofertilizers for sustainable agriculture: Enhancing plant productivity and soil health

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ABSTRACT

Sustainable agriculture focuses on maintaining the soil health, minimizing environmental impact, and promoting plant productivity. Biofertilizers, using beneficial microbes, have become a powerful tool in biofertilizer formulations, enhancing plant productivity and soil health. Microbial consortia, composed of bacteria, fungi, and algae, play a crucial role in biofertilizer formulations by improving soil health and structure, converting atmospheric nitrogen into plant-accessible forms, breaking down insoluble phosphorus, mobilizing micronutrients, and promoting plant growth through growth-regulating hormones and bio control. Benefits of microbial consortia include enhanced plant productivity, reduced environmental impact, soil health restoration and resilience to environmental stress. However, their effectiveness can be affected by factors like environmental conditions, storage and microbial species compatibility. Careful formulation and application of microbial consortia are essential for their success. Regulatory approval is crucial for large-scale implementation and understanding the interactions between different microbes is necessary to design effective consortia that maximize benefits and minimize negative outcomes. This review emphasizes the crucial role of beneficial soil microorganisms in managing the rhizosphere, promoting plant growth and yield through a cost-effective, non-toxic, and eco-friendly approach.

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INTRODUCTION

Modern agriculture heavily relies on hybrid seeds and high-yielding varieties that are highly responsive to chemical fertilizers and irrigation. However, the excessive use of synthetic fertilizers has led to soil pollution, soil contamination, and depletion of essential plant nutrients and organic matter. This has also reduced soil fertility and increased crop disease risk. By 2020, the demand for nutrients will be 28.8 million tons, while their availability will be only 21.6 million tons, causing an energy crisis and increasing fertilizer costs. This is particularly concerning for small and marginal farmers, as the gap between nutrient removal and supplies worsens (Kumar *et al*., 2017). Microbial inoculants, also known as biofertilizers, play a crucial role in managing integrated nutrient systems and sustaining agricultural productivity. These inoculants contain living microorganisms that colonize the rhizosphere, promoting plant growth and converting insoluble elements into soluble forms. These beneficial microorganisms improve microflora, soil health, plant growth, disease control, and pest protection. Biofertilizers contain beneficial microbial inoculants like nitrogen fixer, phosphate, sulphur, zinc solubilizer (VAM), and plant growth-promoting rhizobacteria. These bacteria act as biopesticides and biocontrol agents, enhancing the overall health of the environment (Labuschagne *et al*., 2010)

Biopesticides uses beneficial microorganisms to control insects, but availability is a major constraint. Biopesticides come from plants, animals, bacteria and minerals and are classified into biochemical, plant, and microbial pesticides. 90% of all biopesticides are used globally, with *Bacillus thuringiensis* (Bt) being the most commercially successful. Modern agriculture requires biopesticides and biofertilizers for safe and residue-free crop production. Government and non-government organizations should promote entrepreneurs for biofertilizer and biopesticide production to meet this demand (Seenivasagan *et al*., 2021). The Food and Agriculture Organization (FAO) predicts that the world's population will reach nine billion by 2050, requiring significant agricultural production to ensure food security. To achieve this, factors like environmental conditions and fertile soil availability are crucial. Chemical fertilizers have been used since the mid-20th century to provide nutrients like phosphorus, nitrogen, and potassium to plants. However, only a small percentage of these nutrients are used by plants, and a larger percentage is precipitated by metal cations in the soil. The excessive and inappropriate use of chemical fertilizers also leads to environmental issues, causing farmers to advocate for environmentally friendly agricultural practices. Scientists are now focusing on agrarian sustainability using beneficial soil microorganisms instead of chemical fertilizers and pesticides (Fasusi *et al*., 2021 Yadav *et al*., 2019).

Biofertilizers for sustainable agriculture

Biofertilizers are preparations containing algae, fungi, and bacteria that support plant growth and increase crop yield. These microbes improve soil chemical and biological characteristics by fixing nitrogen, cellulolytic activity, or phosphate. When applied to seeds, plant surfaces, roots, or soil, they inhabit the rhizosphere, enhancing nutrient bioavailability, promoting plant growth, and increasing soil microflora. *Rhizobium* has symbiotic associations with legume roots (Umesha *et al*., 2018). Broad-spectrum biofertilizers including blue-green algae, *Rhizobium*, and *Azolla*, are crop-specific bio inoculants. They include *Azospirillum*, *Azotobacter*, PSB, VAM, and *Anabaena*, which act as nitrogen-fixing cyanobacteria and plant growth-promoting rhizobacteria. PGPR inhibits phytohormones and phytoparasites, aiding plants in withstanding heavy metal contaminations and pollutants (Saharan *et al*., 2011; Tak *et al*., 2013). Biofertilizers are eco-friendly, cost-effective, and can be produced in bulk on farms. They increase crop yield by 10-40% and maintain up to 50% nitrogen content. Continuous application for 3-4 years retains fertility and improves soil texture, pH, and other properties (Gopalakrishnan *et al*., 2011; Breitkreuz *et al*., 2020).

Classification of biofertilizers

Several microorganisms are being utilized in the production of biofertilizers, based on their nature and function (Figure 1). *Rhizobium*, a soil habitat bacterium, colonizes legume roots and fixes atmospheric nitrogen symbiotically. They are the most efficient biofertilizer due to their ability to form nodules in legumes. *Azotobacter*, a species of *Azotobacter*, is the dominant inhabitant in arable soils capable of fixing nitrogen. *Azospirillum lipoferum* and *A. brasilense* are primary inhabitants of soil, rhizosphere, and root cortex of graminaceous plants, developing associative symbiotic relationships with these plants. Cyanobacteria, both free-living and symbiotic, have been harnessed in rice cultivation in India. The benefits of algalization could be 20-30 kg N/ha under ideal conditions, but the labour-oriented methodology for preparing BGA biofertilizer is a limitation. Azolla, a free-floating water fern, fixes atmospheric nitrogen in association with nitrogen-fixing blue green alga *Anabaena azollae*, contributing 40-60 kg N/ha per rice crop. Phosphate solubilizing microorganisms (PSM) involve soil bacteria and fungi secreting organic acids and lowering pH to dissolve bound phosphates in soil. Increased yields of wheat and potato were demonstrated through inoculation of peat-based cultures of *Bacillus polymyxa* and *Pseudomonas striata*. AM fungi transfer nutrients from soil milleu to root cortex cells via intracellular obligate fungal endosymbionts of the genera *Glomus*, *Gigaspora*, *Acaulospora*, *Sclerocysts*, and *Endogone*. These fungi possess vesicles for storage of nutrients and arbuscles for funnelling them into the root system. Silicate solubilizing bacteria (SSB) degrade silicates and aluminium silicates, producing organic acids that play a dual role in silicate weathering. PGPR, or plant growth promoting rhizobacteria, promote growth through suppression of plant disease, improved nutrient acquisition, or phytohormone production. Species of *Pseudomonas* and *Bacillus* produce phytohormones or growth regulators that increase the absorptive surface of plant roots for water and nutrient uptake.

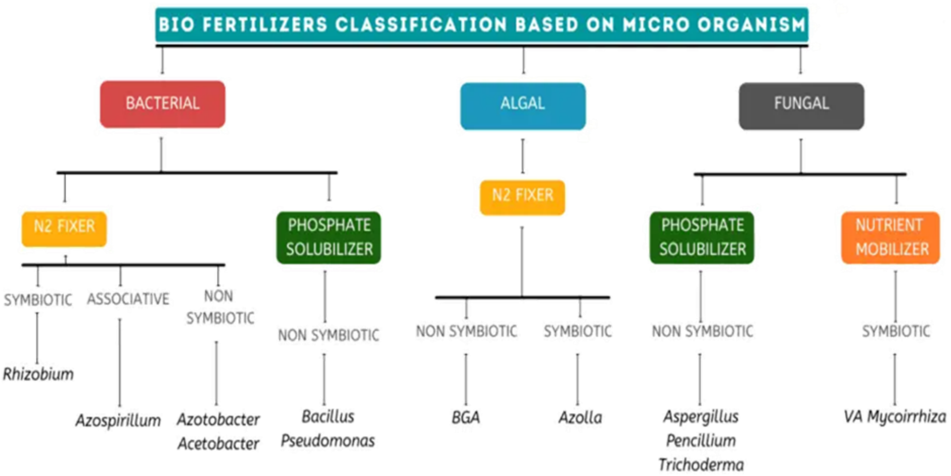

Figure 1. *Classification of microorganisms used in the production of biofertilizers.*

Nitrogen-fixing microbes

Rhizobiaceae microorganisms including *Rhizobium*, *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium* and *Sinorhizobium* are symbiotic nitrogen fixers found in plant root noodles. They fix atmospheric nitrogen in leguminous plants, which is used to synthesize vitamins, amino acids, and other nitrogenous compounds. *Rhizobia's* role in nitrogen fixation reduces dependency on chemical nitrogen fertilizers and is crucial for sustainable agriculture crop rotation strategies (Saha *et al*., 2018).

Phosphorus solubilizing microbes

Phosphorus, a macronutrient, is crucial for plant development and productivity. It is often present in high concentrations as phosphate, either organic or inorganic. Inorganic phosphate is immobilized in insoluble salts, and solubilization involves local acidification or alkalinization. This phenomenon is observed in some plant species (Table 1). Organic phosphate, the largest soil phosphate pool, requires transformation by microorganisms like phosphatases and phytases for absorption by plants. Phosphate solubilizing and mineralizing characteristics are found in some species of *Pseudomonas*, *Cyanobacteria* and *Bacillus* (Fasusi *et al*., 2021; Billah *et al*., 2019).

Potassium solubilizing microbes

Potassium is a crucial macronutrient that regulates various enzyme activities, including those of amylases, which play a crucial role in coordinating root shoot ratio (Kour *et al*., 2019). Potassium deficiency in plants leads to root development issues, increased pathogen susceptibility, and reduced growth. Soil microorganisms like *Bacillus mucilaginous*, *Azotobacter chroococcum* and *Rhizobium* spp. can solubilize potassium, increasing plant productivity in various crops. Inoculation of wheat with a potassium solubilizing strain of *Bacillus edaphicus* has shown significant growth improvements in roots and shoots compared to uninoculated plants. Potassium solubilizing microorganisms promote plant productivity and soil fertility by producing organic acids, which are increased through plant inoculation, leading to increased yield and growth (Etesami *et al*., 2017).

Sulphur oxidizing microbes

Sulphur is a crucial macronutrient for plants, essential for their growth and yield. It is part of amino acids and regulates enzyme activity. A deficiency in sulphur leads to low nitrogen metabolism, chlorosis, and low lipid percentage. Soil contains both organic and inorganic sulphur, with the inorganic form being primarily absorbed by plants. Sulphur-oxidizing microbes, such as *Xanthobacter*, *Alcaligenes*, *Bacillus* and *Pseudomonas*, convert organic sulphur into inorganic forms, promoting plant growth (da Silva Junior *et al*., 2018).

Zinc solubilizing microbes

Zinc deficiency in plants leads to reduced leaf size, chlorosis, increased heat and light stress, and pathogenic attacks. The use of zinc fertilizers poses environmental threats. Alternatives like zinc solubilizing microorganisms, such as *Pseudomonas* spp., *Rhizobium* spp., *Bacillus aryabhattai*, *Thiobacillus thioxidans* and *Azospirillum* spp., are gaining popularity (Ijaz *et al*., 2019). *Bacillus aryabhattai* enhances zinc uptake in maize, promoting better growth and mitigating yield loss compared to uninoculated plants. Zinc solubilizing bacteria *Rhizobium*, *Azospirillum*, and *Pseudomonas* also increase zinc content in wheat, enhancing nutrient uptake and resulting in better quality production (Bhatt *et al*., 2020).

Table 1. Rhizobacteria used in the production of biofertilizer, biocontrol traits, and their effect on plant productivity (Fasusi *et al*., 2021).

Microbial Strains	Plant growth promoting traits	Biocontrol traits	Effect of plant productivity
Bradyrhizobium sp.	Production of siderophore, production of indole acetic acid, nitrogen fixation, and phosphate solubilization	Production of antibiotics, secretion of an enzyme that can degrade the cell wall of plant–pathogen.	Increases. growth parameters and seed yield in mungbeans plant
Rhizobium meliloti	Production of siderophore and nitrogen fixation	Production of antibiotics against phytopathogens and production of chitinases	Increases peanuts growth, yield attributes, quality of pods, and efficiency in the use of nitrogen
R. leguminosarum	Phosphate solubilization	Production of antibiotics, secretion of an enzyme that can degrade the cell wall of plant pathogens.	Increases growth of soybean and yield performance under drought stress
Bacillus spp.	Production of phytohormone, such as auxin,	Formation of endospore and biochemical compound against phytopathogens, induces systemic resistance.	Increases strawberry fresh and dry weight parameters, increases yield over the control plant
Acidothiobacillus ferooxidans	Potassium solubilization	NA	Increases pumpkin growth parameters, yield, and oil composition
Pseudomonas spp.	Production of ACC deaminase phosphate solubilization, ammonia production, production of IAA	Production of hydrogen cyanide, siderophore production	Enhances growth and yields in tomato plants

Plant Growth Promoting Rhizobacteria (PGPR)

Soil inoculants, or microbial inoculants, are farm applications that promote plant growth by promoting beneficial microbes that form symbiotic associations with crop plants (Babalola *et al*., 2010). Inoculants like nitrogen fixers and phosphate solubilizers (PGPR) stimulate growth regulators in plants, enhancing nutrition and growth. These bacteria are classified as biofertilizers and rhizobacteria that promote plant growth. PGPR inoculants work as specialists in biocontrol, biopesticides, and biofertilizers, alternating with chemical fertilizers and pesticides as biofertilizers and antagonists of phytopathogens. They generate various growth regulators and mobilize nutrients in soils, stimulating plant growth. The action mechanisms are not fully known but include nitrogen fixation, organic phosphate and inorganic phosphate solubilization, phytohormones, and siderophores development (Ahmad *et al*., 2006) and PGPR inoculant strains control phytopathogens, improve soil structure and bioremediate contaminated soils by sequestering toxic heavy metals and destroying xenobiotic compounds. They include species like *Azotobacter*, *Azospirillum*, *Agrobacterium*, *Burkholderia*, *Bacillus*, *Clostridium*, *Erwinia*, *Xanthomonas*, *Klebsiella*, *Flavobacterium*, *Micrococcus Paenibacillus macerans*, *Rhizobium*, *Pseudomonas*, *Serratia*, *and Rhodospirrilum*. These strains help improve plant defense, improve soil structure, and destroy pesticides (Glick *et al*., 2012).

Carrier based biofertilizers

The carrier is a crucial group of inoculants used to deliver the appropriate volume of PGPM in a superior physiological state. These carriers can be organic, inorganic, or synthetic and are chosen based on their properties such as availability, low cost, easy use, package ability, and mixability. The carrier also needs to allow gas exchange, especially oxygen, which must have a high water-holding capacity and increased organic matter content. The physical form of biofertilizer is characterized by the carrier used. Soil carrier materials include coal clays, peat, inert materials, organic materials, and inorganic soil. Liquid carriers include organic oils, oil-in-water suspensions, broth cultures, and minerals (Table 2). The carrier material must be non-toxic for both bacterial inoculants and plants. The final choice of carrier also considers properties such as survival during storage, microbial multiplication, planting machinery and cost (Ben Rebah *et al*., 2002).

Biopesticides

Biopesticides are produced from naturally occurring substances and they are gaining global attention as a new tool for controlling pest species like weeds, plant diseases and insects. These eco-friendly pesticides are produced from microorganisms, plants and animals. They contain microbial products and phytochemicals, by-products (semiochemicals) and live species (natural enemies) to control pests in an eco-friendly manner (Cheng *et al*., 2010). Biopesticides are categorized into three main categories: (i) pest-controlled microorganisms (microbial pesticides), (ii) naturally occurring pest-controlled substances (biochemical pesticides), and (iii) plant-controlled pesticides with added genetic material (PIPs). Biopesticides, natural or organically inferred agents, have seen a 10% global increase in use annually. They offer environmentally friendly pest management, similar to chemical pesticides, but require correct formulation and usage for effective control (Lacey *et al*., 2011).

Microbial pesticides

Microbial pesticides are early-developed and genetically modified organisms that develop pest-specific toxins that cause disease and prevent the development of other microorganisms through antagonism or nontoxic mechanisms. These include bioinsecticides (Bt), bioherbicides (*Phytophthora*), and bio fungicides (*Pseudomonas*, *Trichoderma*, and *Bacillus*). They are commonly used to control weeds, pestiferous insects, and plant pathogens biologically. In the market, 74% are guaranteed by bacterial biopesticides, 10% by fungal biopesticides, 10% by viral biopesticides, 8% by predator biopesticides, and 3% by others for a wide range of crops. Microbial pesticides can suppress different target pests by generating toxic metabolites or other modes. They are generally nonpathogenic and nontoxic to all living organisms (Schunemann *et al*., 2014). Bacterial biopesticides are used to monitor weeds, plant diseases, nematodes and insects. They control pests by delivering toxins, outcompeting and harming pathogens, promoting shoot and root growth, and producing anti-fungal compounds. Examples of bacterial biopesticides includes *Pseudomonas syringae*, *Bacillus thuringiensis* (Bt) and *Streptomyces griseoviridis* (Jisha *et al*., 2013). Fungi biopesticides are used to kill mites, weeds, nematodes, insects, or other fungi. They produce toxins that outcompete targeted pathogens and can paralyze plant pathogens or insects by attacking them. Fungal species like *Paecilomyces fumosoroseus*, *Beauveria bassiana*, *Verticillium lecani*, *Nomuraea rileyi* and *Metarhizium anisopliae* are used in insect control (de Faria *et al*., 2007). Nematodes cause severe crop damage but are advantageous in attacking soil-dwelling insect pests like root weevils

Table 2. Types of microbial inoculants act as biofertilizers.

Materials	Category	Reference
Preservative and Culture media (liquid and powder)	Bacterial cultures (lyophilized)	
Alginate and xanthan gum	Biopolymer	
Black ash, paddy husk, soybean and peanut oils, farmyard manure, plant debris, wheat bran, spent mushroom composts, sugar industry waste, agricultural waste material, coconut shell powder, and teak leaf powder	Waste materials (Plant)	Seenivasagan *et al*. (2021)
Lignite, pressmud, charcoal, inorganic soil, coal, clays and peat	Soils	
Carrageenan, polyacrylamide, calcium sulfate, polysaccharide-like alginate, ground rock phosphate, vermiculite, and perlite	Inert materials	

and cutworms. Nematode biopesticides like *Steinernema* sp. and *Heterorhabditis* sp. are widely used for insect control. Protozoans are single-celled organisms surviving both in soil and water. Most species are parasites of insects, typically feeding on bacteria or organic decay. *Vairimorpha* and *Nosema* are common entomogenous nematodes used as insecticides. Viruses are a family of viral biopesticides believed to infect insects and arthropods related to them. Baculoviridae family is used in many parts of the world for the prevention of destructive caterpillar pests. The two main genera of the *Baculoviridae* family are *Nucleopolyhedro* virus (NPVs) and Granulovirus (GVs). These viruses are valuable for controlling lepidopteran pests causing minimal damage to the targeted species (Koppenhofer *et al*., 2002).

Plant Growth Promoting Microbes (PGPM) in beneficial microbial consortia

Positive plant-microbe interactions, such as PGP rhizobacteria, can improve soil nutrient availability, plant nutrient uptake, and nitrogen cycling. Fungal-derived PGPMs, such as mycorrhizal fungi (AMF, VAM), can establish mutualistic symbiosis with over 80% of vascular plant species, enhancing plant absorption capacity and counteracting biotic and abiotic stresses. Trichoderma, an active ingredient in agricultural products, has multiple beneficial effects on plants and is used extensively in biological and integrated pest management. Recent studies demonstrate the potential of these microbial consortia, rhizobacteria and rhizofungi as plant biostimulants, acting as agricultural probiotics. These interactions can help promote plant growth and support the growth of plants ((Lorito and Woo, 2015; Kong *et al*., 2018).

Trichoderma: The evolving MBCA with multiple plant beneficial effects

Trichoderma strains have been shown to be effective biofertilizers, biostimulants, and bio-enhancers of crop resistance to both biotic and abiotic stresses. The PGP effect, a symbiotic interaction, has been demonstrated to be the result of *Trichoderma's* role in solubilizing phosphate and micronutrients, mediated by siderophores and secondary metabolites. This effect can improve plant development by increasing seed germination, chlorophyll content and yield, and enhancing the use of NPK and micronutrients (Samolski *et al*., 2012). *Trichoderma* spp. produce over 250 metabolic products, including cell wall degrading enzymes, peptides, secondary metabolites, and other proteins. These bioactive compounds can affect the plant response to other microbes, improving defense mechanisms and stimulating growth and development, especially at the root level. Synergistic effects on biocontrol have been found in many combinations of diverse strains, metabolites and mixtures of bioactive compounds originating from *Trichoderma* and other microbes or plants, suggesting a wealth of possibilities for developing a new generation of biostimulants (Manganiello *et al*., 2018)

Azotobacter: Rhizocompetent stress tolerant N_2 free-living bacteria

Azotobacter is a free-living species that directly influences nutrition in agroecosystems by fixing nitrogen, increasing soil levels for plants. It can form heat and desiccation-resistant cysts, providing long shelf-life inoculants and tolerance to drought and salinity stress. *Azotobacter* can withstand biotic and abiotic stresses while positively interacting with other microorganisms and plants. Many commercial biofertilizer products contain *Azotobacter* as active ingredients, often in combination with fungi, actinomycetes and other bacteria. *Azotobacter* strains secrete growth-promoting substances like phytohormones, vitamins, and antifungal metabolites. Phosphate solubilization and Fe mobilization have been demonstrated under abiotic stress conditions. *Azotobacter*-mediated synthesis of superoxide dismutase, catalase, proline and high levels of 1-aminocyclopropane-1-carboxylate activity can influence plant health and benefit various crops like tomato and maize. Rice, wheat and sorghum (Viscardi *et al*., 2016; Glick, 2014)

Agricultural probiotics: Microbial consortia to enhance PGP efficacy

Rhizosphere engineering involves using microbial inoculants to mimic native soil structures, promoting the recovery of beneficial microbial groups linked to soil fertility and replenishing the natural microbiome reduced by crop domestication. These treatments can activate nitrogen fixation, phosphate solubilization, siderophore, phytohormone and exopolysaccharide production, which enhance growth and protect plants from abiotic stresses. Although knowledge on the survival of microbial inoculants is limited, rhizosphere competent bacteria and fungi can establish close associations with native macrobiotic and soil fauna. Synthetic bacteria-fungi consortia have the potential to establish novel microbial communities, and co-applications of different microbes may activate new PGP effects not obtained by using single specie (Wargo & Hogan, 2006). Plant microbiome engineering involves identifying and cultivating potential PGPMs, analyzing components, evaluating compatibility, determining cause and effects, developing appropriate formulation recipes and distribution technology and providing technical support to end-users. Studies on *Trichoderma* and *Azotobacter* suggest that these fungi and bacteria could be functionally complementary in a PGP consortium, although their effects on the rhizosphere microbiota have not been fully understood. The *Trichoderma-Azotobacter* consortia could be integrated with botanical and inorganic compounds, seaweeds, polymers, and animal-derived products to create effective and reliable beneficial plant products. Omics studies can reveal mechanisms regulating these interactions and provide new knowledge for improving the next generation of plant biostimulants. The global biopesticide market is growing due to changing agricultural legislations, increased demand for biological/organic products, and conversions to integrated pest management and organic farming systems. The new frontier for plant biostimulants should capitalize on beneficial associations between microorganisms and compounds, building on a deeper understanding of plant-microbe interactions (Ventorino *et al*., 2018).

Conclusion

Integrating microbial consortia into biofertilizers for sustainable agriculture has significant potential in improving plant productivity and soil health. By combining beneficial microorganisms, these consortia support plant growth through nutrient cycling, disease suppression, and growth promotion. This reduces reliance on chemical fertilizers, which are harmful to the environment and human health. Microbial consortia-based biofertilizers contribute to long-term sustainability by improving soil structure, increasing nutrient availability, and promoting plant resilience against environmental stresses. However, further research is needed to optimize formulation and application, ensure stability, effectiveness, and scalability, and tailor the use to specific crops, soil types, and environmental conditions. Overall, integrating microbial consortia into biofertilizers is a promising and eco-friendly strategy for enhancing agricultural productivity while maintaining soil health, aligning with sustainable agriculture principles.

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Conceptualization, Methodology, Software and validation, Formal analysis and investigation, Resources, Data curation, writing-original draft preparation, Writing review and editing, Visualization, Supervision, Project administration, funding acquisition: N.G. and B.T.

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REFERENCES

Ahmad, F., Ahmad, I., & Khan, M. S. (2008). Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. *Microbiological Research*, 163(2), 173-181.

Babalola, O. O. (2010). Beneficial bacteria of agricultural importance. *Biotechnology Letters*, 32, 1559-1570.

Bhatt, K., & Maheshwari, D. K. (2020). Zinc solubilizing bacteria (*Bacillus megaterium*) with multifarious plant growth promoting activities alleviates growth in *Capsicum annuum* L. *3 Biotech*, 10(2), 36.

Billah, M., Khan, M., Bano, A., Hassan, T. U., Munir, A., & Gurmani, A. R. (2019). Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture. *Geomicrobiology Journal*, *36*(10), 904-916.

Breitkreuz, C., Buscot, F., Tarkka, M., & Reitz, T. (2020). Shifts between and among populations of wheat rhizosphere *Pseudomonas*, *Streptomyces* and *Phyllobacterium* suggest consistent phosphate mobilization at different wheat growth stages under abiotic stress. *Frontiers in Microbiology*, *10*, 3109.

Cheng, X. L., Liu, C. J., & Yao, J. W. (2010). The current status, development trend and strategy of the bio-pesticide industry in China. *Hubei Agricultural Sciences*, 49(9), 2287-2290.

Da Silva Junior, S., Stamford, N. P., Oliveira, W. S., Silva, E. V. N., de Rosalia e Silva Santos, C. E., de Freitas, A. D. S., & da Silva, V. S. G. (2018). Microbial biofertilizer increases nutrient uptake on grape (*Vitis labrusca* L.) grown in an alkaline soil reclaimed by sulfur and Acidithiobacillus'. *Australian Journal of Crop Science*, *12*(10), 1695-1701.

De Faria, M. R., & Wraight, S. P. (2007). Mycoinsecticides and mycoacaricides: a comprehensive list with worldwide coverage and international classification of formulation types. *Biological Control*, *43*(3), 237-256.

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.

Fasusi, O. A., Cruz, C., & Babalola, O. O. (2021). Agricultural sustainability: microbial biofertilizers in rhizosphere management. *Agriculture*, 11(2), 163.

Glick, B. R. (2012). Plant growth promoting bacteria: mechanisms and applications. *Scientifica*, *2012*(1), 963401.

Gopalakrishnan, S., Rao, G. R., Humayun, P., Rao, V. R., Alekhya, G., Jacob, S., & Rupela, O. (2011). Efficacy of botanical extracts and entomopathogens on control of *Helicoverpa armigera* and *Spodoptera litura*. *African Journal of Biotechnology*, *10*(73), 16667-16673.

Ijaz, M., Ali, Q., Ashraf, S., Kamran, M., & Rehman, A. (2019). Development of future bioformulations for sustainable agriculture. Microbiome in plant health and disease: challenges and opportunities, 421-446.

Jisha, V. N., Smitha, R. B., & Benjamin, S. (2013). An overview on the crystal toxins from Bacillus thuringiensis. *Advances in Microbiology*, *3*(05), 462.

Kong, W., Meldgin, D. R., Collins, J. J., & Lu, T. (2018). Designing microbial consortia with defined social interactions. *Nature Chemical Biology*, *14*(8), 821-829.

Kour, D., Rana, K. L., Yadav, A. N., Yadav, N., Kumar, M., Kumar, V., & Saxena, A. K. (2020). Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatalysis and Agricultural Biotechnology*, *23*, 101487.

Kumar, R., Kumawat, N., & Sahu, Y. K. (2017). Role of biofertilizers in agriculture. *Popular Kheti*, *5*(4), 63-66.

Labuschagne, N., Pretorius, T., & Idris, A. H. (2011). Plant growth promoting rhizobacteria as biocontrol agents against soil-borne plant diseases. Plant growth and health promoting bacteria, 211-230.

Lorito, M., Woo, S. L., Harman, G. E., & Monte, E. (2010). Translational research on Trichoderma: from'omics to the field. *Annual Review of Phytopathology*, *48*(1), 395-417.

Manganiello, G., Sacco, A., Ercolano, M. R., Vinale, F., Lanzuise, S., Pascale, A., & Woo, S. L. (2018). Modulation of tomato response to *Rhizoctonia solani* by *Trichoderma harzianum* and its secondary metabolite harzianic acid. *Frontiers in Microbiology*, *9*, 1966.

Ben Rebah, F. B., Tyagi, R. D., & Prevost, D. (2002). Wastewater sludge as a substrate for growth and carrier for rhizobia: the effect of storage conditions on survival of *Sinorhizobium meliloti*. *Bioresource Technology*, *83*(2), 145-151.

Saha, B., Saha, S., Roy, P. D., Padhan, D., Pati, S., & Hazra, G. C. (2018). Microbial transformation of sulphur: an approach to combat the sulphur deficiencies in agricultural soils. Role of rhizospheric microbes in soil: Volume 2: Nutrient Management and Crop Improvement, 77-97.

Saharan, B. S., & Nehra, V. (2011). Plant growth promoting rhizobacteria: a critical review. *Life Science and Medical Research*, *21*(1), 30.

Samolski, I., Rincon, A. M., Pinzon, L. M., Viterbo, A., & Monte, E. (2012). The qid74 gene from *Trichoderma harzianum* has a role in root architecture and plant biofertilization. *Microbiology*, *158*(1), 129-138.

Schunemann, R., Knaak, N., & Fiuza, L. M. (2014). Mode of action and specificity of *Bacillus thuringiensis* toxins in the control of caterpillars and stink bugs in soybean culture. *International Scholarly Research Notices, 1*, 135675.

Seenivasagan, R., & Babalola, O. O. (2021). Utilization of microbial consortia as biofertilizers and biopesticides for the production of feasible agricultural product. *Biology*, *10*(11), 1111.

Umesha, S., Singh, P. K., & Singh, R. P. (2018). Microbial biotechnology and sustainable agriculture. In Biotechnology for sustainable agriculture (pp. 185-205). Woodhead Publishing.

Ventorino, V., Sannino, F., Piccolo, A., Cafaro, V., Carotenuto, R., & Pepe, O. (2014). Methylobacterium populi VP2: plant growth promoting bacterium isolated from a highly polluted environment for polycyclic aromatic hydrocarbon (PAH) biodegradation. *The Scientific World Journal*, *1*, 931793.

Viscardi, S., Ventorino, V., Duran, P., Maggio, A., De Pascale, S., Mora, M. L., & Pepe, O. (2016). Assessment of plant growth promoting activities and abiotic stress tolerance of *Azotobacter chroococcum* strains for a potential use in sustainable agriculture. *Journal of Soil Science and Plant Nutrition*, *16*(3), 848-863.

Wargo, M. J., & Hogan, D. A. (2006). Fungal—bacterial interactions: a mixed bag of mingling microbes. *Current Opinion in Microbiology*, *9*(4), 359-364.

Yadav, K. K., & Smritikana Sarkar, S. S. (2019). Biofertilizers, impact on soil fertility and crop productivity under sustainable agriculture.