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Soil Microbes: Silent Heroes of Nature that Boast up the Soil Health and Ultimately Accelerate the Human Welfare

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Authors' contributions

This work was carried out in collaboration among all authors. Author SAJ designed the study, collected literature review and wrote the first draft of the manuscript. Author MA added more literature review and updated new information. Author SC gave constructive suggestions. Authors AJA, AH and KN revised and proofread the draft of the manuscript. Authors MSH, MZ and MMHM reconstructed the table and organized the references & citations. Authors MK and MF checked grammar & language. All authors read and approved the final manuscript.

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Review Article

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Abstract

The major factor influencing agricultural output is the productivity of the soil, which is a complex system of biological, chemical, and physical interactions driven by microorganisms. Certain microorganisms, like mycorrhizal fungi, phosphorus-solubilizing bacteria, and symbiotic bacteria that fix nitrogen, are known to improve the health of mineral soil and have a significant effect on plant performance. Ecology, pharmacology, food production, biofuel or energy generation, or the development of medicines, nitrogen and carbon fixation, biocontrol agents, bioremediation, organic matter decomposition, and soil formation are all areas in which microorganisms are essential. Soil formation, nitrogen and carbon fixation, biocontrol agents, bioremediation, pharmaceuticals, food sources, biofuel or energy production, drug or medicine development, and the breakdown of organic matter are just a few of the numerous processes that depend on microbes. The balance shifts from degeneration to regeneration due to beneficial microorganisms. Because of their diversity and number, microorganisms, which include 1 trillion species, or 60% of all living things play a significant role in Earth's life. They are essential to ecosystems and human health, yet their contributions are typically overlooked or underestimated. The purpose of this study is to illustrate their contributions to sustainable development and human well-being. It also seeks to educate researchers and/or scientists about the useful applications of microbial communities. It is suggested that study on microbes should be given top attention in order to improve human well-being because they have the ability to ensure the functioning of the Earth's ecosystem and increase human welfare.

Keywords: Microorganisms; food production; ecosystem; biofertilizer; human welfare.

1. Introduction

Plant-soil interactions are vital for many physiological processes. Effective microorganisms may positively impact plant development by modifying the atmosphere under which microorganisms live in a certain soil, according to numerous published studies (Higa & Parr, 1994). Effective bacteria may also affect nutrient availability (Kleiber et al., 2014). Soil microbes encompass a vast array of species, with each group specializing in different functions. Bacteria, for example, are adept at breaking down organic matter, while fungi excel at forming symbiotic relationships with plants. Soil microbes act as ecosystem engineers, modifying their physical and chemical surroundings. They influence soil structure, nutrient availability, and water retention (Huang, 2023; Ranjan et al, 2025).

Soil microorganisms, for example bacteria, fungus, viruses, archaea, protozoa, and tiny algae, are crucial for sustaining soil fertility (Islam et al., 2020). They are crucial to the soil ecosystem's, for the breakdown of organic matter, the cycling of nutrients, and the defense against diseases that spread via the soil (Khaziev, 2011). The variety of these microbes is essential to the stability of agricultural systems and the production of nutritious crops.

The complexity of soil environments, shaped by their unique physical and chemical properties, gives rise to a vast diversity of soil microorganisms. However, this diversity is under constant threat from global environmental changes including climate change, intensive agriculture, and land-use alterations. The loss of soil microbial diversity can have profound implications for ecosystem services such as nutrient cycling and disease resistance, which are essential for crop growth and health (Chen et al., 2024; Lazutin et al., 2025).

Because soil ecosystems are complicated due to their unique physical and chemical characteristics, a diversified soil microorganisms can be found. However, changes in the global environment, including land-use shifts, intensive agriculture, and climate change, constantly threaten this variety (Li et al., 2016). Crop growth and health depend on ecosystem services like disease resistance and nutrient cycling. Ecosystem services may be significantly impacted by the reduction of soil microbial diversity (Zhao et al., 2024).

"A soil lacking microorganisms is dead soil," according to renowned microbiologist Jacob Lipman. Soil is not a dead substance. Fertile soil has a range of microbiological species, such as actinomycetes, fungi, bacteria, algae, and protozoa. They mostly live in the rhizospheric soil, where they break down organic matter to create humus, which improves soil fertility and holds nutrients (Dominati et al., 2010).

Microorganisms are definitely valuable when it comes to soil fertility. Although the majority of people believe that bacteria cause illness, they actually serve a variety of beneficial purposes in the biosphere, which is the region of our planet that contains soil, water, and air. Most importantly, beneficial bacteria help break down hazardous waste and other contaminants and improve soil fertility (Kawalekar, 2013). Numerous studies on their impact on boosting soil productivity have been conducted in recent years. Thus the paper is to explore their effects on soil fertility, plant nutrition, and above all crop productivity.

Soils contain a range of microorganisms. Up to one billion bacterial cells, tens of thousands of species, up to 200 m of fungal hyphae, and a diversity of mites, nematodes, and arthropods can all be found in one gram of soil (Wagg et al., 2014). Microbes need oxygen, water, the right soil chemistry for growth, the right soil temperature, and a lot of food to survive and proliferate, just like the majority of other living organisms. There will be fewer soil microorganisms if one of the conditions is not fulfilled.

Fig. 1. Different types of soil microbes (Created with BioRender.com)

The role of soil microbes in optimizing nutrient utilization and preserving biological fertility for sustainable crop production:

1. Soil nitrogen fixation and improved nutrient uptake
2. Preventing the spread of pathogens in soil
3. Quicken the breakdown of organic waste, composting, and leftovers
4. Biocomposting using natural microbes
5. Increase the organic compound's helpful minerals
6. Increase the native microorganisms' activity
7. Increase crop yield and plant strength
8. Benefits of EM in livestock farming
9. Reduce environmental pollution
10. Bioremediation

Soil microbes also produce simple organic molecules for plant uptake, complex heavy metals to limit plant uptake, dissolve insoluble nutrient sources, break down organic wastes and residues, suppress soil-borne pathogens, recycle and increase plant nutrient availability, break down toxicants like pesticides, and produce antibiotics and other bioactive compounds (Higa and Parr, 1994).

Three mechanisms are frequently proposed to explain how microorganisms can stimulate plant growth:

1. Modifying the signaling of plant hormones (Verbon and Liberman, 2016)
2. Preventing or combating harmful microbial strains (Mendes et al., 2013); and
3. Increasing soil-based nutrients' bioavailability (van der Heijden et al., 2008).

Bacteria improve the natural environment for a number of reasons. Such as:

Microorganisms fixing nitrogen: The process that transforms inert N_2 into physiologically beneficial NH_3 is known as biological nitrogen fixing. In nature, only N-fixing rhizobia bacteria (Rhizobiaceae, α-Proteobacteria) promote the aforementioned process (Sørensen and Sessitsch, 2007). With rising input costs and a fundamental shift towards understanding soil health and its impact on human health, our food production methodology is poised for a significant advancement into biological systems to enhance both yield and quality rather than merely augmenting yield potential and maximizing productivity.

Due to increased accountability, farmers must find a balance between productivity and sustainability (Herridge et al., 2008). In order to maintain agricultural systems' sustainability, profitability, and productivity while protecting our ecosystem, restoring or efficiently recycling nutrient reserves drained from the soil requires cooperation with nearby ecosystems and natural resources. It is wise to start using both efficient management techniques and methods to take advantage of soil biodiversity (Graham & Vance, 2000). Biological nitrogen fixation (BNF) is a suitable and effective place to start in this situation.

Microorganisms' solubilization of phosphorus: Phosphate solubilizing microorganisms (PSMs) are bacteria or fungi that may break down insoluble forms of phosphorus, such as phosphates, in the soil and make it easily soluble for plants to ingest, according to Rawat et al. (2020). One of the essential minerals needed for plant growth and development is phosphorus (P), which makes up 1.2% of the dry weight of a plant. It is one of the mineral nutrients that most frequently restricts crop growth, second only to nitrogen (Azziz et al., 2012, Tak et al., 2012).

Only 0.1% of the 0.05% (w/w) of phosphorus that is normally present in soil may be utilized by plants (Zhu et al., 2011). Historically, Phosphorus fertilizers have been used to solve the problem of soil phosphorus deficiency (Sharma et al., 2013). Adding more inorganic fertilizers than is often done to prevent this impact, however, might result in environmental issues including groundwater contamination and river eutrophication since plants cannot absorb the majority of the phosphorus in fertilizers (Kang et al., 2011). Investigating management techniques that can boost crop yields, improve the effectiveness of phosphorus fertilization, and lessen the damage that soil phosphorus loss causes to the ecosystem is therefore essential. Microorganisms in the soil aid in the uptake of nutrients by plants (Chernov & Semenov, 2021). The conversion of insoluble soil nutrients is one of the many biological processes they participate in (Babalola and Glick, 2012). Some are able to solubilize and mineralize insoluble soil phosphorus for plant growth. Only microbial P-solubilization and mineralization can increase plant-available phosphorus, aside from chemical fertilization. According to Bhattacharyya and Jha (2012), a variety of soil and rhizosphere microorganisms effectively release phosphorus from the total amount of soil phosphorus in the natural environment through solubilization and mineralization. The term Phosphorus Solubilizing Microorganisms (PSM) refers to this class of microorganisms. Many fungi and bacteria that live in soil can mobilize phosphorus in plants and solubilize it in vitro. For plant absorption, PSM makes soil-insoluble phosphorus more bioavailable. Agricultural practices based on saline-alkaline soil are made possible by halophilic or salt-tolerant soil microorganisms that can also breakdown insoluble phosphorus (Zhu et al., 2011).

Therefore, inoculating soil or crops with phosphate solubilizing/mineralizing microorganisms is an effective way to increase plant uptake of phosphorus and reduce the application of chemical fertilizers that are harmful to our planet (Alori et al., 2012).

Enhancement of fertility with mycorrhizal fungi: Among all the basic partnerships discovered in nature, mycorrhiza form symbiotic relationships between plants and fungi. It is found in all soil types where plants can grow and facilitating the absorption of water and nutrients (Huey et al., 2020). Approximately 80% of terrestrial plants that are distributed throughout different habitats exhibit AM association (Quilambo, 2003). This symbiotic association played a major role in the early territorialization and diversification of terrestrial plants.

The relationship between AM fungus and plants is referred to as a bidirectional mutualistic symbiotic interaction, in which both provide nutrient resources to one another (Kiers et al., 2011). Mycorrhizal fungi provide more than 80% of the nitrogen (N) and 100% of the phosphorus (P) necessary for plant growth, even though fungi consume photosynthetically fixed organic carbon-based compounds from plants (Smith and Read, 2008) (Luginbuehl et al., 2017). Beyond just exchanging nutrients, this interaction promoted plant colonization by increasing resilience and resistant to diseases, drought, and poor soil conditions (Quilambo, 2003).

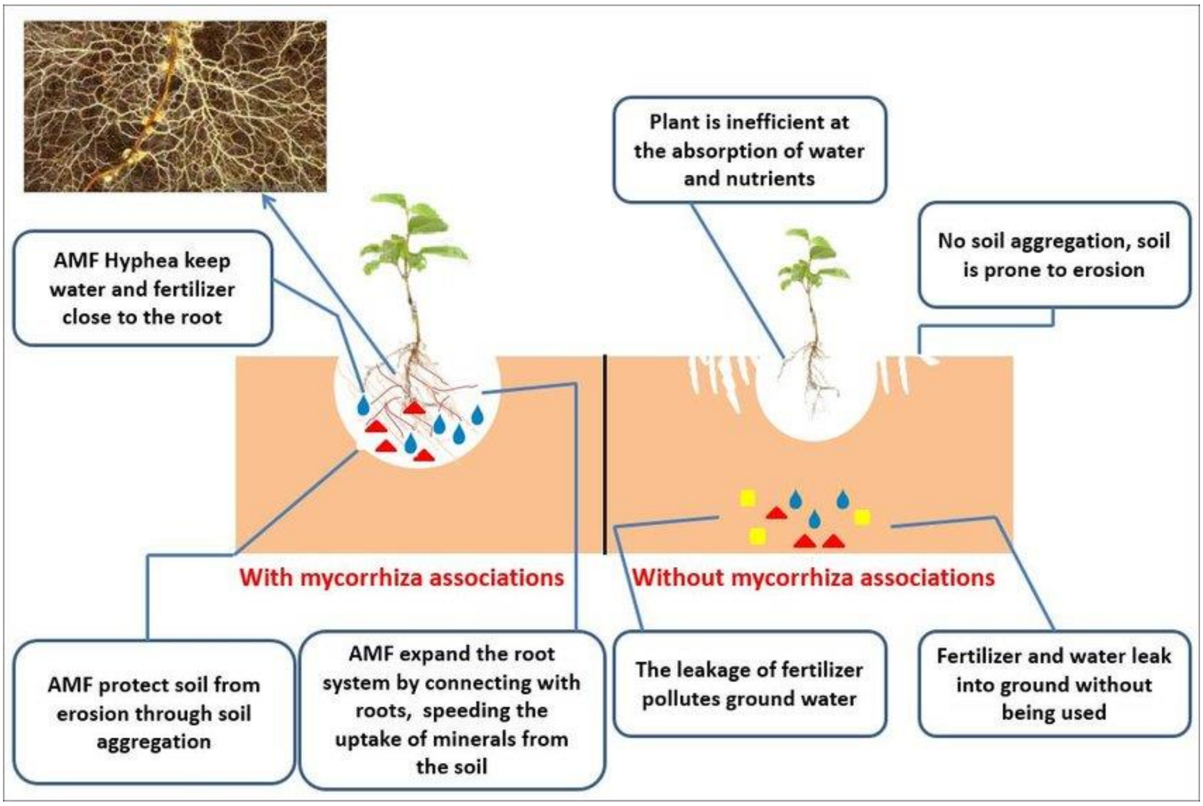

Fig. 2. Association of mycorrhizal fungi with plants (Ullah et al., 2019)

2. Soil microbial Status of Some Agro-Ecological Zones (AEZs) in Bangladesh

Nahar et al. (2020) conducted a study with the purpose of determining the soil microbial populations that were present in Bangladesh's various AEZs. Soil samples (0–15 cm depth) have been collected using GPS recording in the districts of AEZ-8 (Kishoreganj), AEZ-21 (Kishoreganj), AEZ-10 (Faridpur Sadar), AEZ-16 (Munshiganj), AEZ-19 (Cumilla), AEZ-22 (Habiganj and Moulovibazar), and AEZ-27 (Rangpur). The spread plate count method was employed to quantify the populations of beneficial and total bacteria, fungi, and actinomycetes cultivated in specific media. According to the study report, Kishoreganj (AEZ-21) had highest total number of bacteria among the examined AEZs, followed by Habiganj (AEZ-22) and Faridpur Sadar (AEZ-10). Cumilla had a larger total fungal population (AEZ-19).

According to Sahoo et al. (2015), soil microorganisms are essential for improving soil quality and impacting agricultural production. By changing the properties of the soil, either directly or indirectly, it regulated its fertility. One of the most important aspects of the agricultural system is the interaction between bacteria and plants. In the future, this group might be able to assist in achieving the goal of sustainable agriculture. Bacteria, fungus, mosses, and liverwort were among the many microorganisms found in soil. The three primary types of soil microorganisms are bacteria, fungi, and actinomycetes. In order to improve water availability, nutrient uptake, and resistance to biotic and abiotic stressors, rhizospheric bacteria must establish connections with plants.

3. Ecological Balance among Plants, Soil and Microbes

Biofertilizer is also used in organic farming systems, little is known about the mechanisms underlying the selection of plant cultivars and microbial inoculants (Bender et al., 2016). Using organic fertilizers effectively increases agricultural yield by improving the physical, chemical, or biological properties of the soil and the fertilizer's efficacy (Tiwari et al., 2021). Plants engage with soil-dwelling organisms through a range of ecological interactions, such as commensal, reciprocal, cooperative, exploitative, and competitive partnerships. In contemporary science, reducing pathogens such as infection, herbivory, or abiotic stress conditions has been the aim of numerous plant-based interactions.

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8-15 tons of bacteria, worms, protozoa, nematodes, and arthropods are believed to be present in soils (Hoorman, 2010). The shiftment of microbial population can indicate the beginning of soil improvement or deterioration because they drastically alter the physical and chemical composition of soil material. One example is the turnover rate of microbial biomass.

4. Soil Health and Crop Productivity

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The three primary types of soil microorganisms are bacteria, fungi, and actinomycetes. Partnerships between rhizospheric bacteria and plants improve water availability, nutrient intake, and tolerance to biotic and abiotic stresses. Microbes control the chemical and physical properties of the soil and are an indicator of the biological activity taking place there. For all nutrient cycles and plant nutrition, microbes are essential part of the soil. Microbiological diversity and soil processes are negatively impacted by temperature variations, low water content, human activity, and grazing.

The interaction between bacteria, roots, and soil is rather permanent and advantageous. Certain bacteria negatively affect the rhizosphere and impede plant growth and development, according to Ahmad et al. (2008). Intense farming and the negative effects of fertilizers reduce the diversity of soil microbes.

5. Management of Soil Organic Matter and Soil Fertility

Soil organic matter is essential for maintaining production by improving nutrient and water-use efficiency by enhancing soil physical properties, increasing biological activity, and elevating crop quality. Soil productivity depends on maintaining soil organic carbon levels, which are also connected to global warming through the greenhouse effect. The most important component that needs to be taken care of in order to restore soil health through the addition of organic materials and the application of different management techniques is soil organic matter (Biswas & Kole, 2018)

Interaction between soil microbes: The diverse range of microorganisms that live in soil facilitates several essential soil processes that are critical to crop health. Furthermore, the effectiveness of soil bacteria can be impacted by either antagonistic or synergistic interactions.

The production and use of bioinoculants may likewise be impacted by such a characteristic. According to Artursson et al. (2006), one of the most important interactions between different kinds of soil microorganisms is that between arbuscular mycorrhizal fungus and soil bacteria. By influencing rhizodeposition and root development, AM fungus can change the makeup of soil microorganisms. Rhizodeposition and root growth are significant sources of nutrients and secondary metabolites for the soil bacteria that live in the mycorrhizosphere (Gryndler 2000, Miransari and Mackenzie, 2011).

Factors like (1) competition for nutrients and (2) the highly specific responses of certain bacteria to specific AM species, which arise from the production of specific AM fungal products like polysaccharides, also impact the significance of interactions between AM and soil bacteria (Artursson and Jansson 2003, Toljander et al., 2006). Numerous researchers have demonstrated that AM fungi, such as species of *Pseudomonas, Bacillus, Paeinibacills, Rhizobium,* and *Entrobater*, have a beneficial interaction with PGPR. Compared to Gram-negative bacteria, Gram-positive bacteria appear to be more closely linked to AM fungus. PGPR may be able to colonise AM hypha, according to studies by Hildebrandt et al. (2002) and Artursson et al. (2006).

Microbial biomass: Soil microbial biomass is the portion of soil that controls the transformation of organic matter and helps with the cycling of nutrients and energy (Gregorich et al., 1994; Turco et al., 1994). Numerous studies have shown a tight relationship between the amount of mineralized nitrogen, the pace of decomposition, and the amount of microbial biomass in the soil (Carter et al., 1999). Microbial biomass has a favorable correlation with grain yield in organic farming, but not in conventional farming. Ultimately, soil microbial biomass helps to stabilize and organize the soil (Fliessbach et al., 2000).

6. Microbial Roles in Major Biogeochemical Cycles and other Processes

i. **Carbon Cycle:** Microbes play a crucial role in regulating the flow of carbon in the environment through a number of activities. The breakdown of organic compounds by bacteria and fungi releases carbon dioxide into the soil or environment. This process is essential for the turnover of carbon in both terrestrial and aquatic ecosystems (Falkowski et al., 2008).

ii. Cyanobacteria and algae play a major role in carbon fixation and lay the foundation for various food webs by converting atmospheric CO2 into organic carbon through photosynthesis (van der Heijden et al., 2008).

iii. **Nitrogen Cycle:** The nitrogen cycle is significantly influenced by microbial processes:

iv. The process by which symbiotic bacteria like *Rhizobium* and free-living organisms like *Azotobacter* transform atmospheric nitrogen (N_2) into ammonia (NH_3) that plants may use is known as nitrogen fixation. In order to increase nitrogen bioavailability for plants, ammonia-oxidizing bacteria like *Nitrosomonas* and *Nitrobacter* oxidise ammonia to nitrite (NO_2^-) and nitrate (NO_3^-). This process is known as nitrification. Denitrifying bacteria, such as *Pseudomonas*, are crucial for resupplying nitrogen in the environment because they convert nitrates (NO_3^-) into N_2 gas. This process is essential to the nitrogen balance in ecosystems (Falkowski et al., 2008).

v. According to Kuypers et al. (2018), ammonification is the process by which bacteria convert organic nitrogen into ammonia, completing the recycling of nitrogen molecules in ecosystems.

vi. **Phosphorus Cycle:** Phosphorus cycling includes microbial alteration of both organic and inorganic forms. Van der Heijden et al. (2008) state that certain bacteria, including Bacillus and *Pseudomonas*, have the ability to solubilise insoluble phosphates into forms that plants can absorb.

vii. **Importance to Ecosystems:** The capacity of microbes to cycle nutrients is crucial for maintaining the resilience of ecosystems, boosting primary productivity, and addressing environmental issues including eutrophication and greenhouse gas emissions. Microbial sulphate reduction, for example, keeps harmful sulphur compounds from building up, and microbial nitrogen fixation boosts agricultural productivity by replenishing soil nitrogen levels (Kuypers et al., 2018).

viii. **Microorganisms in Aquatic Carbon Sequestration:** Phytoplankton and Cyanobacteria: These photosynthetic microorganisms are crucial for converting CO2 into organic carbon in freshwater and marine habitats. These organisms are the foundation of the marine food web and the "biological pump," which helps transfer carbon from surface waters to deeper oceanic layers (Jiao et al., 2010).

ix. **Methanotrophs and Carbon Sequestration:** Methane Oxidation: By turning methane (CH_4), a significant greenhouse gas, into CO_2, methanotrophic bacteria lessen its effects. The CO2 can subsequently be absorbed by photosynthesis or other carbon sequestration activities (Falkowski et al., 2008).

x. **Carbon Sequestration in Permafrost and Wetlands:** Microbes in Peatlands Wetlands and peatlands are significant carbon storage because of the way their low-oxygen, water-saturated ecosystems prevent microbial breakdown activities. Certain microbial communities in these settings aid in the stabilisation of organic carbon (Freeman et al., 2001).

xi. **Microbial Activity in Permafrost:** In permafrost settings, microbes have two functions: first, their breakdown activities can release CH_4 and CO_2, and second, some microbial processes can stabilise soil carbon during freezing temperatures (Turetsky et al., 2020).

xii. **Biochar and Microbial Interaction Soil Amendment:** Biochar, a carbon-rich byproduct of pyrolysing biomass, promotes increased soil microbial activity. Microbes stabilise soil organic matter and boost its ability to sequester carbon by integrating biochar into it (Lehmann et al., 2011).

xiii. **Role of Microbes in case of Greenhouse Gas:** Methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), and other greenhouse gases (GHGs) are transformed and mitigated in large part by microbes. Because their actions can either accelerate or ameliorate climate change depending on environmental conditions and metabolic pathways, they play important roles in biogeochemical cycles. Take Microbial Reduction of Greenhouse Gases, for instance. Methanotrophs, or methane-oxidizing bacteria, such Methylosinus and Methylocystis, are essential for lowering atmospheric CH_4 because they transform it into CO_2 when oxygen is present. This method reduces methane emissions in aquatic systems, soils, and wetlands (Conrad, 2009).

7. Plant Growth-promoting Rhizobacteria (PGPR)

Plant growth-promoting rhizobacteria, or PGPR, are free-living bacteria that colonize plant roots to promote plant growth. Perez-Montano et al. (2014), Vocciante et al. (2022), and Bhanse et al. (2022) state that PGPR can use their own metabolism (fixing nitrogen, producing hormones, or solubilizing phosphates), directly impact plant metabolism (increasing the uptake of water and minerals), enhance root development, boost the plant's enzymatic activity, and "help" other beneficial microorganisms to increase their effects on the plant.

Through the evolution of fungal cell wall lysing enzymes, aseptic-activity compounds, and systemic reactions in host plants, they biocontrol pathogens by competing with illnesses for scarce nutrients. By enhancing plant fitness, stress tolerance, and pollutant cleanup, PGPR may enable plants to thrive in the face of abiotic stress. According to Oleńska et al.'s (2020) study, obtaining further data and deepening our comprehension of the characteristics of the bacteria that support plant growth may encourage and inspire the development of innovative solutions that employ PGPR in extremely diverse habitats and climates.

8. Integrated Nutrient Management for Improving Soil Organic Carbon

Integrated nutrient management (INM), which entails maximizing the benefits of all accessible organic, inorganic, and biological sources in a coherent way to maintain goal productivity, can be used to improve soil fertility and plant nutrition availability. FYM, or farmyard manure, is the most common kind of organic fertilizer. It includes all secondary and micronutrients as well as around 0.5% nitrogen, 0.2% phosphorus, and 0.5% potassium. Additionally, it improves the general health of the soil and its ability to retain rainwater. Restoring soil fertility and improving its physical and biological properties require efficient management of crop waste.

Crop leftovers can be converted into high-value manure by using enrichment methods like phosphocompost and vermicompost. Particularly in arid areas with little fertilizer application, biofertilizers such as Rhizobium, Azotobacter, Azospirillum, blue-green algae, phosphate-solubilizing organisms, VAM, and cellulose decomposers are essential elements. According to Swarup (1998), the content of soil organic carbon in rice soils rose from less than 5 g per kg in 1973 to roughly 8 g per kg in 1994 as a result of integrated nutrient management. Balanced fertilization raised the amount of soil organic carbon (SOC) in the top 42 cm of soil by 8 tons per hectare at a rate of 0.25 tons per hectare annually, according to long-term fertilizer tests conducted in India.

9. On-Farm Strategies for Improving Soil Organic Carbon

It is feasible to improve SOC by increasing CO2 uptake and reducing emissions through the use of suitable on-farm methods and land management techniques. Based on the crops grown and the outcomes of soil tests, a nutrient management package tailored to each farmer's field can be created. Because tillage increases oxidation and erosion rates, it accelerates the loss of organic materials. As a result, tillage should only disturb the soil to the ideal degree required for soil aeration, weed control, and sowing. Reducing tillage slows down the rate at which crop residues break down on the soil's surface and reduces erosion losses (Pandey and Singh 2012).

10. Microbial Strains That Promote Plant Growth by Enhancing N, P, and S Nutrition

For potential growth-promoting strains to be successfully used in agriculture, it is essential to show that they can colonize the rhizospheric environment, be successfully reintroduced to plants, and help mobilize nutrients that support plant growth. The ability of candidate strains to enhance nutrient uptake and promote plant development can be evaluated using assays for plant-microbe interactions (Ahemad and Kibret, 2014). Research in this area has come a long way, particularly in the area of nitrogen-fixing Rhizobia. Decades of research into the best inoculation methods have focused on identifying the optimal combinations of plant genotypes and rhizobia strains appropriate for particular climates and soils (Lindstrom et al., 2010).

When discussing the taxonomy of nitrogen-fixing symbioses, it is important to keep in mind that nitrogenase genes are found in a range of bacterial taxa (Gyaneshwar et al., 2011). Additionally, N2-fixing bacterial strains have been found in non-leguminous plants (Santi et al., 2013), suggesting that interactions between plants and microbes (other than Rhizobia and legumes) may also aid in nitrogen fixation (Mus et al., 2016). According to Shaharoona et al. (2008), higher yields in plants injected with specific bacterial strains indicate that microbial mobilization of various nitrogen sources can promote plant growth.

The ability of the fungus Glomus intraradices to transfer organic nitrogen to plants was demonstrated by Thirkell et al. (2016). Future studies could examine other fungal strains that possess this capability and identify the genes and mechanisms at play. The literature contains numerous reports of bacterial and fungal strains that may solubilise inorganic phosphorus and mineralise organic phosphorus (Plassard et al., 2011; Ahemad and Kibret, 2014).

Microbial promotion of plant development occurs in a number of ways, even though many P-mobilizing strains have also been identified as growth-promoting microbes. It is occasionally yet debatable whether P-mobilization is responsible for the increase in plant growth observed with these strains (Richardson and Simpson, 2011).

Studies on a Pseudomonas strain that stimulates plant growth have employed genetic deletion of the sulfonate monooxygenase enzyme to demonstrate that organic-S mineralization contributes to a portion of the growth-promoting phenotype (Kertesz and Mirleau, 2004).

Many bacterial isolates that have been genomically sequenced and can be put back together to form SynComs are currently being gathered by researchers (Bai et al., 2015; Xia et al., 2015).

11. Nitrogen-supplying Biofertilizers

Numerous free-living bacteria found in soil or in symbiotic relationships with plants fix a significant amount of atmospheric nitrogen (78% by volume). A profile of some microorganisms that fix atmospheric nitrogen and are used in biofertilizers is shown in Table 1.

Table 1. A profile of different biofertilizers which fix nitrogen

Sl	Biofertilizer	Function/Contribution	Limitations	Used for crops
1	*Rhizobium*	i. Fixation of 50-100 kg N/ha ii. 10-35% increase in yield iii. Leaves residual N	i. Fixation only with legumes symbiotically ii. Visible effect not reflected in traditional area, Needs optimum P& Mo demands iii. High organic matter	i. Pulse & legumes like chickpea red gram, pea, lentil, black gram etc., ii. Oil seed legumes like soybean & groundnut, iii. Forage legumes like clover and lucerne, iv. Tree legumes like Leucaena
2	*Azotobacte*r- (non-symbiotic)	i. Fixation of 20-25 kg N/ha	i. Visible effect not reflected in traditional area, Needs optimum P& Mo Demands High organic matter	i. Wheat, maize, cotton, sorghum, sugarcane, pearl millet, rice and vegetables and several other crops
3	*Azospirillum* (Associative)	i. 10-15% increase in yield ii. Production of growth promoting substances iii. Fixation of 20-30 kg N/ha		i. For all cereals, sorghum millets etc.
4	Blue Green Algae or Cyanobacteria (Phototrophic) in yield	i. Production of growth promoting substances	i. Effective only in submerged rice ii. Demands bright	i. Flooded rice
5	Azolla (Symbiotic)	i. Fixation of 30-100 kg N/ha ii. Yield increases 10-25%	i. Survival difficult at high temperature	i. Only for Flooded rice

(Tilak K.V. B. R., 1991)

12. Positive Impacts of Rhizobacteria

In order to meet agricultural demands and guarantee future food security, sustainable agriculture is essential in today's globe. Our conventional farming practices are insufficient for a number of reasons. To accomplish the same goal, we urgently need to build a durable and efficient mechanism. Our agricultural needs that traditional methods have not been able to meet could be satisfied by sustainable agriculture. Specialized methods are used in this kind of agriculture to make the most use of environmental resources without sacrificing them. As a component of specialized formation, biological techniques could be a useful substitute to solve the shortcomings of conventional techniques. This type of farming is beneficial since it makes use of natural resources without endangering future generations.

Plant roots are colonized by a rich and varied population of microorganisms, such as fungus, bacteria, and actinomycetes. These microorganisms are a group of advantageous bacteria that exist naturally and are used as inoculants to encourage the growth and development of plants (Ahmad et al. 2008). These microbial communities have several traits that interest modern researchers and decision-makers. These microbiological communities also improve crop quality, soil health, and soil quality. In the form of root exudates, organic matter draws a wide range of microorganisms and serves as their habitat. Competent rhizobacteria live in the rhizosphere zone of plant roots and react to root exudates through chemotactic processes. Some microorganisms live close to plants and engage in a variety of interactions (Singh et al. 2011).

Certain signaling molecules facilitate molecular-level communication. Root nodules may develop in response to plant-microbe compatibility, providing the ideal conditions for bacteria to fix atmospheric molecular nitrogen (Masciarelli et al. 2014). The microbial community is made up of particular microbe groups that have traits that encourage plant growth. These microorganisms may live in the rhizosphere and promote the growth of plants. The sustainability of many ecosystems is greatly aided by soil microorganisms. These microorganisms influence the dynamics of soil organic matter, control nutrient cycling, and enhance nutrient acquisition efficiency. The symbiotic microorganisms help plants acquire nutrients and water more efficiently. These microbial partnerships also control nutrient cycle, mineralization, and decomposition.

Rhizobium**:** Around 14 million tonnes of nitrogen are fixed in legume root nodules annually by *Rhizobium* worldwide, accounting for more than half of the 30 million tonnes of nitrogen fixation generated in industry annually. The yield of oilseed legumes and pulses has now been demonstrated to be significantly increased by efficient rhizobial cultures (Table 2), and various trials carried out in India have demonstrated that inoculation with effective rhizobia can save approximately 50% of nitrogenous fertilizer (Subbarao et al., 1993).

Table 2. Quantity of nitrogen fixed of legumes due to *Rhizobium* inoculation

SI	Crop	N fixed (%)
1.	Chickpea	85-110
2.	Cowpea	80-85
3.	Groundnut	50-60
4.	Lentil	90-100
5.	Mung bean	50-55
6.	Pigeon pea	168
7.	Urdbean	50-55

(Subbarao et al., 1993)

Azotobacter**:** There is a strong correlation between *Azotobacter*'s nitrogen fixing capacity and its carbohydrate intake. Mulberries, grains, vegetables, and other foods benefit from *Azotobacter*. *Azotobacter* inoculation can reduce the amount of N fertilizer applied by about 25–50% (Bagyaraj, 1992).

Table 3. Cane yield due to *Azotobacter* inoculation

Sl	N levels	Cane yield (t ha^{-1})	
		Azotobacter	**Control**
1.	150 kg N ha^{-1}	175.58	143.47
2.	200 kg N ha^{-1}	195.92	172.77
3.	250 kg N ha^{-1}	196.03	1177.35

(Bagyaraj, 1992)

Table 4. Yield response of cereals to *Azospirillum* inoculation at different levels of nitrogen application in the field

Sl	Crop	N applied (kg ha^{-1})	Grain yield (t ha^{-1})		
			Control	Inoculated	Increase (t ha^{-1})
1	Rice	0	2.93	3.08	0.15
		30	3.52	3.98	0.46
		45	3.93	4.54	0.61
		60	4.45	4.85	0.40
2	Wheat	0	3.78	3.90	1.12
		40	4.54	4.58	0.94
		80	4.94	5.75	0.81
		120	4.95	6.29	1.34
3	Maize	0	3.43	3.90	0.47
		33	3.95	5.81	1.86
		66	3.98	7.20	3.22
		100	4.15	7.27	3.12

(Wani, 1992)

***Azospirillum* and *Acetobacter diazotrophicus*:** Numerous investigations looked at the majority of the most recent *Azospirillum* sp. inoculation trials. Forage grasses, barley, ragi, sorghum, pearl millet, maize, and numerous more crops benefit from *Azospirillum* inoculation. A number of crops have shown yield increases of up to 11% (Wani, 1992) (Table 4). Baldani et al. identified a novel Brazilian bacterium in 1986 called *Herbaspirillum*, which is taxonomically linked to *Azospirillum*. It has the ability to restore atmospheric nitrogen and has been linked to grasses, according to research. Sugarcane, sweet potatoes, and sweet sorghum are among the plants commonly linked to the saccharophilic bacterium *Acetobacter diazotrophicus*. Before being combined with the carrier material, the bacteria may be cultivated in a nitrogen-free malate medium in order to inoculate sugarcane.

13. Biofertilizer aiding Phosphorous Nutrition Phosphate Solubilizing Microorganism

It is possible to mass multiply the P-solubilizing bacteria on Pikovaskai broth and combine them with the carrier material. Researchers at IARI, New Delhi, have shown that using phosphate-solubilizing microorganisms in addition to rock phosphate can produce outcomes that are similar to those obtained with superphosphate (Tilak, 1991).

There are phosphate-solubilizing rhizobacteria everywhere, and the populations of these microorganisms vary depending on the kind of soil. By producing organic acids and phosphatases, microorganisms that solubilize phosphate (PSM), such as bacteria and fungi, aid in its mobilization. Phosphate-solubilizing microorganisms include a wide range of bacterial and fungal taxa (Yadav et al., 2014).

The plant growth-promoting rhizobacteria (PGPR) category includes phosphate-solubilizing bacteria, which have a major impact on plant development and growth (Naseem & Bano, 2014). Either cation chelation or a drop in pH can cause phosphate to become soluble. Depending on the properties of the soil, phosphate-solubilizing microorganisms have different effects. In phosphorus-deficient situations, the majority of plants associated with rhizobacteria improve soil phosphorus uptake. As biofertilizers, phosphate-solubilizing microorganisms (PSM) encourage plant growth and provide phosphorus to plants in a sustainable manner (Meena et al., 2015; Naseem & Bano, 2014).

The primary mechanism in this process are the generation of organic acids, especially acid phosphatase, and the drop in pH. The organic acids released from PSB reduce the surrounding pH and facilitate the release of phosphate ions by H+. Among the significant acids that plants make are malic acid, succinic acid, oxalic acid, and others. These organic acids compete with one another for binding sites in the soil and available phosphorus, which is essential for plant absorption. 2-keto gluconic acid is the most effective acid that phosphate-solubilizing microbes can make. Many bacteria are capable of solubilizing phosphate (Istina et al., 2015).

Table 5. Use of phosphate solubilizing microorganisms on crops

Sl	**Crop**	**Yield (kg ha^{-1})**		
		Uninoculated	**Inoculated**	**% increase**
1	Rice	1937	2161	11.50
		2050	2300	12.20
2	Wheat	4100	4811	17.30
		4786	5584	16.60
3	Chickpea	2370	2920	23.20
4	Pea	2169	2717	25.20
5	Soybean	1050	1786	70.00
6	Potato	23320	37330	60.00

(Tilak, 1991)

14. Plant-microbe Interactions that Assist in Biocontrol

Plant roots offer an ecological habitat for soil bacteria, which are nourished by root exudates and lysates. Mutualistic interactions between plants and helpful microbes are common and can improve plant nutrition and/or increase a plant's resistance to biotic and abiotic stress. This results in increased plant growth and proliferation and provides a competitive advantage in all circumstances (Haney et al., 2015). Many endophytic bacteria and free-living rhizobacteria on the root surface and rhizosphere absorb the nutrients supplied by the host and release metabolite chemicals into the soil to help avoid bacterial or fungal-induced plant illnesses (Gray & Smith, 2005; Kiely et al., 2006).

For example, this indirect relationship between the microbes and plants enhances the delivery of minerals and other nutrients that impact plant growth through air nitrogen fixation or phosphorous solubilization (Bowen & Rovira, 1999). The relationship between plants and a group of biocontrol bacteria also indirectly stimulates plant growth by preventing the development and activity of illnesses (Chet & Chernin, 2003; Bais et al., 2006). Furthermore, by controlling soil fitness and accelerating plant growth for example, by generating auxin microbes can directly contribute to the growth of plants (Welbaum et al., 2004).

This could also include abiotic stress reduction. Despite having different biological rhizosphere habitats, some of the beneficial microorganisms employ comparable mechanisms to encourage plant growth and prevent dangerous illnesses (Dobbelaere, 2003; Glick, 1995; Sturz & Christie, 2003). One microbial biocontrol agent that can be used to control butterfly caterpillars is the bacteria Bacillus Thuringiensis, also known as Bt. To treat plant diseases, the fungus Trichoderma is being developed as a biological control. The majority of baculoviruses used as biological control agents belong to the genus Nucleopolyhedrovirus.

It has previously been demonstrated that the nematophagous fungus *Paecilomyces lilacinus* can be used to efficiently control root-knot nematodes (Mittal et al., 1995). To effectively manage the root-knot nematode, combinations of nematicidial microbial agents, such as Bradyrhizobium haponicum, Trichoderma pseudokoningii, and Glomus mossease, have been implemented in the field (Oyekanmi EO et al., 2007). Bacillus frimus and P. lilacinus have also been effectively used together to eliminate the root-knot nematode's egg mass.

15. *Agrobacterium tumefaciens*: A Natural Tool for Plant Transformation

Agrobacterium tumefaciens: an organic plant transformation tool for Plant transformation, which is facilitated by the soil plant pathogenic bacteria *Agrobacterium tumefaciens,* is the most widely used method for introducing foreign genes into plant cells and then producing transgenic plants. *A. tumefaciens*, which naturally infects the wound sites of dicotyledonous plants, causes crown gall tumors. Crown gall has been linked to this bacteria for about 90 years (Smith and Townsend, 1907).

For a number of reasons, this neoplastic disease and the organism that causes it have been the subject of several investigations since then. The transfer of genes from *Agrobacterium tumefaciens* to plant cells involves a number of important mechanisms.(1) colonization of bacteria; (2) stimulation of the virulence system of bacteria; (3) creation of the T-DNA transfer complex; (4) transfer of T-DNA; and (5) integration of T-DNA into the plant genome.

16. Microbes as Biofertilizers

By adding nutrients to the soil, they protect the plant from pests and diseases while also boosting crop productivity and soil fertility. They have been shown to enhance the growth of the root system, extend its lifespan, degrade harmful compounds, increase seedling survival, and reduce the time until flowering (Youssef & Eissa, 2014). Another benefit is that after three to four years of consistent use, biofertilizers are no longer necessary because the parental inocula are sufficient for growth and multiplication (Bumandalai & Tserennadmid, 2019). By adding nutrients to the soil, they protect the plant from pests and diseases while also boosting crop productivity and soil fertility. They have been shown to enhance the growth of the root system, extend its lifespan, degrade harmful compounds, increase seedling survival, and reduce the time until flowering (Youssef et al, 2014).

Another benefit is that after three to four years of consistent use, biofertilizers are no longer necessary because the parental inocula are sufficient for growth and multiplication (Bumandalai & Tserennadmid, 2019). 17 essential elements are required for a plant to grow and develop properly. These include relatively high levels of potassium (K), phosphorus (P), and nitrogen (N) (Mishra & Dash, 2014). Along with molds and fungi, a variety of microorganisms are commonly used as biofertilizers, including cyanobacteria, phosphate-solubilizing bacteria, and nitrogen-fixing soil bacteria (Umesha, 2018). Likewise, bacteria that produce phytohormones are used in the composition of biofertilizer. They provide the plant growth-promoting elements such vitamins, amino acids, and indole acetic acid (IAA). Additionally, they maintain crop yield while boosting soil fertility and productivity (Parikh & James, 2012).

17. Monitoring of Microbes

Soil microbes can be monitored using a variety of methods, including:

1. **Soil sampling:** Soil samples are collected from different areas of a field or garden and sent to a laboratory for analysis. The lab can test for microbial activity, disease risks, pH, nutrient levels, and more.
2. **Microbial indicators:** Microbial properties are considered to be some of the most relevant indicators of soil quality (Hopkin, 1998). For example, microbial parameters can be used to monitor soil pollution by heavy metals.
3. **16S rRNA gene amplification:** This sequencing method can identify and classify microorganisms in soil, water, and air samples. It can help assess pollution, contamination, and microbiome profiles.
4. **Soil microbial tests:** These tests use a compound light microscope to identify, measure, and count microbes in soil or compost. The biomass of the microbes can then be calculated.
5. **Microbial biomass:** The total microbial biomass is a quantified total of a large number of fatty acids. Fungi and bacteria make up the largest proportion of this.
6. **Soil metabolomics:** This emerging technology measures the metabolites of important metabolic pathways to characterize soils and evaluate the metabolic status of the soil microbial community. Soil metabolites can also be used as biomarkers for soil contamination.
7. **Microbial biomass carbon:** This is a measure of the carbon contained in the living component of soil organic matter, such as bacteria and fungi.
8. **Crop rotation:** Growing different sets of crops across fields, rather than planting the same year after year, can help soils maintain microbes year-round.

18. Conclusion

Most soil microorganisms are essential to processes that are essential to soil health, human civilization's survival, and life on earth. Since soil microbes have the potential to greatly advance our understanding of plant-soil systems and provide insights into pressing 21st-century issues like environmental change and agricultural sustainability, we should protect them by using integrative methodologies. The bacteria must be carefully chosen, mixed, and prepared in accordance with the requirements for the effective development of biofertilizers.

In addition to being economically and environmentally beneficial, the proper use of fertilization that means a combination of chemical and biological fertilization can significantly boost global food supply.

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.

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Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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