

Harnessing the Power of Soil Microbes for Sustainable Soil Health: A Review

Abstract

The soil microbes, indicator of soil health, are bacteria, fungi, algae, actinomycetes, nematode, and protozoa. They are a dynamic component of soil and performed many beneficial functions in the soil system. They have an important soil function that has fulfilled several useful tasks in the soil system. Most of investigators confirmed that soil microbial activity is very important to improve soil health for healthy crop growth because microorganisms play an important role in building a complex link between plants and soil. Beneficial microorganisms play an important role in sustainable agriculture since they maintain the physical, chemical and biological components of soil in an environmentally friendly way. Soil microbes have the diverse roles encompassing soil structural improvement, facilitating soil aggregation, residues decomposition, nutrient cycling, phytohormone production, disease suppression along with bioremediation and biofertilizers. Microbes help in different biological transformation such as organic matter conversion and nutrient cycling, enhanced the availability of nutrients to the plants. The changes in microbial populations and their activities in various soil conditions are excellent indicators of change in soil health. The bioavailability of chemicals is also an essential issue for soil health. The impact of such substances on soil health is dependent on microbial activities. They play an essential role in decomposing organic matter, cycling nutrients, and fertilizing the soil. Besides, they improve plant growth on various physiological parameters of plants by a number of mechanisms. The review summarizes the literature on harnessing the power of soil microorganisms for sustainable soil health and physico-chemical properties and outlines the significant impact of soil microbes on sustainable agricultural growth, the benefits of microbes in maintaining soil health, and their interactions.

Keywords: Soil microbes; quality indicators; soil health; nutrient cycling

Introduction:

Soil is a finite and non renewable resource because regeneration of soil through

various weathering processes (physical, chemical, and biological) of underlying rock requires geological time (Huber *et al.* 2001). The world's population is growing at an alarming rate, which means that healthy soils will be needed to satisfy the future food supply as land pressure from urbanization, biofuel production, and resource extraction increases. Managing soils sustainably so they can support the necessities of future generations is our main challenge. Before, only the physical and chemical characteristics of soil were valued; now, the function of soil biodiversity in preserving soil fertility and agricultural yield is also taken into consideration. “The status of the health of soil can be indicated by its microorganism’s population dynamics (Kundu, 2025). Healthy soil is an ecosystem with many interconnected parts, with each part functioning to sustain plant, animal, and human lives (Brevik *et al.* 2020). A healthy soil maintains a balance between the health of living organisms residing in or on it, environmental quality, and productivity (Khattoon *et al.*, 2017). Healthy soil is imperative for environmentally sound, productive, and profitable systems of agriculture (Adedayo *et al.*, 2022).

Soil microbes are essential for preserving soil health and promoting sustainable farming methods. Their roles in nutrient cycling, maintenance of soil fertility and microbial biodiversity. Microorganisms such as bacteria, fungi, viruses, archaea, and protists make up soil ecosystems and soil healthy (Carey *et al.*, 2016; Pattnaik *et al.* 2021) and play a crucial role in agricultural ecosystem health and productivity (Fu *et al.* 2023; Khmelevtsova *et al.* 2022). They perform variety of functions, and climate change can disrupt microbiomes and negatively impact changes in specific functions performed by soil microbes (Joshi *et al.* 2019). In a healthy soil-plant system, the soil biota controls nutrient flow, root development, and storage. Before being used by the crop, fertilizer may even go through effective rhizospheric microorganisms (Dubey *et al.* 2019). Use of microbial inoculants and other biostimulants can help to restore microbiomes that have been damaged by climate. Therefore, by understanding effective ways of managing soil microbiomes, it is possible to mitigate the effects of climate stress on nutrient cycling and enhance soil health (Joshi *et al.* 2019).

1. Soil Health

The term "soil health" was first used in the mid-1990s. A number of scientists have provided different definitions of the term, but one of the most widely accepted is "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health, "as put forth by Doran and Safley in 1997 and Panda *et al.*, 2024. Soil health refers to “the ability of the soil to achieve its full potential and be productive under the intended land use” and “healthy soils have favourable physical, chemical and biological properties that promote plant health and maintain environmental quality” (Kundu, 2025). Sustainable soil health refers to maintaining and improving soil's ability to function as a vital living ecosystem, supporting plant growth, water retention, biodiversity, and carbon sequestration, while mitigating climate change and ensuring long-term food security.

Soil microorganism as an indicator of soil health

A variety of soil characteristics, including physical, chemical, and biological indicators, are evaluated in the process of evaluating the quality of soil. “Microorganisms have the

capacity to indicate good soil health. The changes in microbial populations and their activities in various soil conditions act as an excellent indicator of change in soil health” (He *et al.*, 2022). Bacteria, fungi, and protozoa indicators are grouped according to the different soil health parameters of the ecosystem like biodiversity, carbon cycling, nitrogen cycling, biomass, microbial activity, key species, and bioavailability. The indicators are related to the ecosystem (e.g., processes), community (e.g., biomass and biodiversity), or population (e.g., species or functions) levels (Kundu, 2025). Soil microbes are microscopic organisms, including bacteria, fungi, and protozoa, that play a crucial role in maintaining soil health and ecosystem balance. A single gram of soil can contain billions of bacteria, with estimates ranging from 10^8 to 10^{11} individuals (Fierer, 2017).

2. Function of microorganism in the soil health

Enhancing soil quality and promoting plant health through beneficial microorganisms has garnered significant attention in agricultural research, as evidenced by a rich body of literature exploring various aspects of microbial contributions to soil ecosystems and crop productivity (Compant, *et al.*, 2019). Microorganisms are an essential and integral part of living soil influencing various biogeochemical cycles on major nutrients such as carbon, nitrogen, sulphur, phosphorous and other minerals and play superior role in maintaining soil health than other biological component of soil (Sathya, *et al.*, 2016). Soil microbes have the diverse roles encompassing nitrogen fixation, phosphorus solubilization, disease suppression, and improvement of soil structure (Compant, *et al.*, 2019). Soil microorganisms function in supplying and controlling the services that soil ecosystems offer (Dominati *et al.*, 2010). They perform variety of functions, including nutrient cycling, organic matter decomposition, disease suppression, plant growth promotion and resistance to stressors, such as drought and heavy metal pollution (Joshi *et al.*, 2019). By fostering a diverse microbial community, agricultural systems can become more resilient to environmental stresses, such as drought and extreme temperatures, thereby, increasing crop productivity and sustainability (Philippot *et al.*, 2013).

A healthy soil harbours an abundant, active, diverse microbial community which is a key to many soil functions that impact soil productivity, including nutrient cycling and decomposition of organic matter (Kabuyah, 2012). Different microorganisms including phosphate-solubilizing microorganisms (PSMs) strains have been obtained from soil suffering from abiotic stresses either due to salinity (Phour and Sindhu 2022), cold (Mishra *et al.*, 2011), drought (Kour *et al.*, 2020; Kumar and Sindhu 2024), high temperature (Verma *et al.*, 2019), and or heavy metals (Teng *et al.*, 2019; Chaudhary and Sindhu 2024). These Stress-tolerant microbes protect plants against abiotic stresses by increasing nutrient availability, producing siderophore, phytohormones, ACC deaminase, and osmo protectants (like betaine, proline, and glycine), and resulting in improved crop production (Ojuederie *et al.*, 2019; Shah *et al.*, 2021a, b; Vocciante *et al.*, 2022; Kaniganti *et al.*, 2022; Bittencourt *et al.*, 2023).

Table1 Different roles of soil microbes

Sr. No.	Microbes	Role
1.	<i>Cyanobacteria</i>	As a biofertilizers (N fixer)
2.	<i>Rhizophagus clarus</i>	Nitrogen and Phosphorus uptake
3.	<i>Klebsiella</i>	Enhanced plant productivity
4.	<i>Bacillus</i>	Phosphate solubilizing bacteria

5.	<i>Azospirillum</i>	Free living N-Fixing bacteria
6.	<i>Azotobacter</i>	N-cycling and produce vitamins
7.	<i>Penicillium aspergillus</i>	Biodecomposers

2.1 Soil structure and aggregation:

Soil organisms are responsible for many important functions in the soil which in turn improve soil health these include improving soil structure and soil water holding capacity (Alori, *et al.*, 2024). All soil organisms help decompose nutrient rich organic material (decaying plants, animals, and animal waste), which increases soil organic matter that helps to bind soil particles together thus improving soil health (Alori, 2024). Soil biota potentially contribute to soil aggregation in a number of ways (Johnson *et al.*, 2016 and Six *et al.*, 2004). For example, bacteria can exude biopolymers that act as binding agents for aggregates on the micrometre scale (Deng *et al.*, 2015). Microorganisms also affect the physical properties of the soil. Production of extra cellular polysaccharides and other cellular debris by microorganisms help in maintaining soil structure as well as soil health. Thereby, they also affect water holding capacity, infiltration rate, crusting, erodibility, and susceptibility to compaction (Elliott *et al.*, 1996). Changes in microbial populations or activity can precede detectable changes in the soil's physical and chemical properties, thereby providing an early sign of soil improvement or an early warning of soil degradation (Pankhurst *et al.*, 1995). Soil microorganisms like fungi can help to break up compacted soil by using their extra cellular hypha. Thus increasing soil porosity and improve soil aeration, which in turn reduce risks such as waterlogging and soil erosion. Soil Fungi also through their extracellular hypha and secretion of polysaccharides entwining loose soil particles there improving the soil structure and hence soil health (Wei *et al.*, 2024). Plant exudates and microbial byproducts – both considered active organic matter can be sticky substances that help hold soil particles together to form better aggregate (Gasch and DeJong-Hughes 2019).

Soil microorganisms—including bacteria like *Pseudomonas* and *Bacillus*, fungi such as *Mortierella* and *Gigaspora*, algae like *Nostoc* and *Anabaena*, and actinomycetes such as *Streptomyces*—play key roles in improving soil structure. Bacteria are important in producing polysaccharides that cement sand, silt, and clay particles together to form microaggregates and improve soil structure (Hoorman, 2011). They produce substances like extracellular polysaccharides and form networks that bind soil particles into stable aggregates, enhancing soil porosity, stability, and long-term fertility. Soil microorganisms play a critical role in improving soil structure, both by breaking compacted soil and by stabilizing soil aggregates (Gupta and Germida 2015). Fungal hyphae can entangle particles to hold them together (on the micrometre to millimetre scale) and geophagous animals, such as earthworms, grind and remould ingested particles into new aggregates and create bio pores (on the millimetre to centimetre scale) (Blanchart *et al.*, 2009).

Table 2 Roles of soil microorganisms in improving soil physical health and soil quality

Microorganism Group / Species	Role in improving soil physical health and soil quality	Citation
Fungi		
<i>Glomus intraradices</i>	Enhances soil aggregation, porosity, and water retention	Rillig, (2004).

<i>Aspergillus niger</i>	Secretes organic acids improving soil particle cohesion and porosity	Sun <i>et al.</i> , (2015).
Bacteria		
<i>Bacillus subtilis</i>	Produces extracellular polysaccharides enhancing soil aggregation and porosity	Sandhya <i>et al.</i> , (2010).
Actinomycetes		
<i>Streptomyces spp.</i>	Produces filamentous hyphae entangling soil particles and secretes binding compounds	Rillig <i>et al.</i> , (2015).
Algae		
Nostoc spp.	Secretes extracellular polysaccharides that bind soil particles and enhance water retention	Belnap, (2001).
Protozoa		
<i>Acanthamoeba spp.</i>	Grazes on bacteria, enhancing microbial turnover and soil aggregation	Clarholm, M. (1985).
Colpoda spp.	Regulates microbial biomass and nutrient cycling improving soil structure	Bonkowski, M. (2004).

2.2 Decomposition

Decomposition is a mostly microbially mediated process, although its actual rate and extend are influenced by environmental variables, including soil temperature, moisture, oxygen, nitrogen content, the quality and quantity of available carbon substrates as well as soil management (Khatoon *et al.*, 2017). Soil microorganisms, primarily bacteria and fungi, are key decomposers that break down organic matter, releasing essential nutrients like carbon, nitrogen, phosphorus, and sulfur into forms accessible to plants. (Kuzyakov and Blagodatskaya, 2015). Primary decomposition is initiated in part by organisms called primary saprotrophs, in that they release digestive enzymes into their environment to solubilize a source of nutrient, or substrate (Adl, 2003). Arbuscular mycorrhizal plants tend to produce leaf litter with a higher quality (i.e., lower C:N) and greater decomposability relative to ectomycorrhizal plants in temperate ecosystems (Cornelissen *et al.*, 2001; Vesterdal *et al.*, 2012; Phillips *et al.*, 2013). There is positive effects of the combination of *Trichoderma harzianum* and *Phanerochaete chrysosporium* in enhancing lignin degradation and promoting compost maturity, providing a foundation for a deeper understanding of the mechanisms involved in lignin degradation and humification processes influenced by the fungal community during composting, ultimately contributing to the efficient utilization of agricultural waste resources (Zhai *et al.*, 2025). Among the bacteria, members of the order *Actinomycetales* are considered quintessential degraders of complex polysaccharides in soils. Actinomycetes like *Streptomyces* and *Micromonospora* contribute by producing enzymes and stabilizing soil aggregates (Yeager *et al.*, 2017). Actinomycetes are well known as lignocellulose decomposers, its four of the isolates *Micromonospora chalcea*, *Streptomyces roseflavus*, *Nocardiodes fulvus* and *Kibdelosporangium philippinense*. These four highly cellulolytic strains were tested for abilities to decompose rice straw pieces under different incubation conditions (Abdulla and El-Shatoury, 2007). Earthworms contribute to decomposition by fragmenting, incorporating, and mixing residues into the soil, they shows positive effect on the later stages of low-quality residue decomposition (Jiang, *et al.*, 2018).

2.3 Nutrient cycling

Soil microorganisms are crucial for nutrient cycling, transforming and mobilizing essential nutrients like nitrogen, phosphorus, sulfur, and carbon. Nitrogen-fixing bacteria convert atmospheric nitrogen into plant-available forms, while phosphate-solubilizing microbes make phosphorus accessible. Sulfur-oxidizing bacteria cycle sulfur compounds, and decomposer microbes break down organic matter, releasing carbon and other nutrients to maintain soil fertility and support plant growth (Kuypers *et al.*, 2018; Richardson and Simpson, 2011). Different microbial species from various genera have ability of nitrogen fixation such as *Bacillus*, *Azospirillum*, *Pseudomonas*, *Enterobacter*, *Flavobacterium*, *Erwinia*, and *Rhizobium* (Silva *et al.*, 2016). Several organisms could also be powerful agents in the initial weathering of rocks, including fungi, bacteria, cyanobacteria, archaea, and mosses. Those microorganisms cause mineral disaggregation, dissolution, hydration and secondary mineral formation directly or indirectly (Jackson, 2015).

Bacteria from all four groups perform important services related to water dynamics, nutrient cycling, and disease suppression. They are 20–30% efficient at recycling carbon (C) (Hoorman, 2011). Ectomycorrhizal fungi have the enzyme capacity to degrade soil Carbon (Brzostek and Finzi 2011, Burke *et al.*, 2011, Jones *et al.*, 2012, Vaario *et al.*, 2012), there have been few empirical studies to explore if mycorrhizal fungi directly increase soil carbon degradation. Phosphate solubilizing microbes (PSM) such as bacteria and fungi mobilizes it by producing organic acid and phosphatase. Many genera of bacteria and fungi are described as phosphate solubilizing microbes (Yadav *et al.*, 2014). Other beneficial activities of PSMs, such as release of phytohormones, production of ACC deaminase, strengthening of antioxidant system, and induction of systemic resistance, also contribute toward stress mitigation and plant growth promotion under stressful environments (Kumar *et al.*, 2025).

Microalgae can enhance the stability of soil aggregates with the increment of organic matter, nitrogen, phosphorus and pH (6.5–8.5) in the soil (Redmile-Gordon *et al.*, 2020). They can prevent nutrient loss by slowly releasing nitrogen, phosphorus, and potassium to meet the growth needs of plants (Coppens *et al.*, 2016; Sasaki *et al.*, 2020). Algae contribute to nutrient cycling by fixing atmospheric CO₂ through photosynthesis, fixing nitrogen via cyanobacteria, and solubilizing phosphorus and micronutrients to enhance soil fertility. Protozoa aid carbon cycling by decomposing organic matter, participate in nitrogen transformations including nitrification and denitrification, and help mobilize phosphorus and sulfur compounds in soil (Geisen *et al.*, 2019). Soil viruses regulate C and N cycles both directly and indirectly via their interactions with microbial hosts, mainly including shaping the microbial community structure, mediating horizontal gene transfer and microbial metabolism, increasing C and N availability and alleviating nutrient limitations, promoting C and N sequestration, and mitigating climate change (Wu *et al.*, 2025). Other essential elements including P, K, S, Mg, Ca, Fe and a range of trace element micronutrients are derived initially from minerals and released enzymes secreted by microorganisms (Falkowski *et al.*, 2008).

Table 3 Key microbial metabolic processes related to nutrition

Element	Biochemical process	Microbial genes	Soil enzymology literature
Nitrogen	Nitrogen fixation,	nifD, nifH, nifK	

	Protein Depolymerization, Urea catabolism	apr, npr, sub ureA, ureB, ureC	Mader <i>et al.</i> , 2002 Dick <i>et al.</i> , 1988; Bowles <i>et al.</i> , 2014
Phosphorous	Phosphate ester Cleavage, Phosphonate breakdown	phoA, phoD, phoX, ACPase, glpQ, ushA, appA, phyA, phyB phnJ, phnX	Mader <i>et al.</i> , 2002; Garcia-Ruiz <i>et al.</i> , 2008
Sulfur	Sulfate ester cleavage, Sulfonate breakdown	aslA, asfA ssuD	Garcia-Ruiz <i>et al.</i> , 2008

Table 4 Nitrogen and phosphorus cycling mediated by arbuscular mycorrhizal fungi (AMF) and hyphosphere bacteria

Nutrient	AMF	Bacteria or bacteria source	Result(s)	Reference
N	<i>Funneliformis mosseae</i>	<i>Pseudomonas fluorescens</i> JL1	Upregulated nosZ expression, reduced net N ₂ O emission	Li <i>et al.</i> , 2023
	<i>R. irregularis</i>	Live soil microbial inocula	Increased N acquisition	Hestrin <i>et al.</i> , 2019
	<i>R. irregularis</i>	A protist <i>Polysphondylium pallidum</i>	Increased organic N utilization	Rozmos <i>et al.</i> , 2022
P	<i>R. irregularis</i>	<i>Bacillus megaterium</i> C4, <i>Rahnella aquatilis</i> HX2	Enhanced organic P mineralization, increased microbial biomass P	Wang <i>et al.</i> , 2016
	<i>R. irregularis</i>	Phosphate-solubilizing bacterium <i>R. aquatilis</i> HX2	Enhanced organic P mineralization	Zhang <i>et al.</i> , 2018
	<i>Rhizophagus intraradices</i>	Bacterial filtrate Filtered washings of soil inocula	Enhanced P turnover	Wang <i>et al.</i> , 2023

2.4 Bioremediation: Nature's Clean-Up Crew :

Bioremediation is a biological mechanism of recycling wastes in to another form that can used and reused by other organisms (Abatenh, 2017). Bioremediation is occurred naturally and encouraged with in addition of living things and fertilizers. Bioremediation technology is principally based on biodegradation. It refer to complete removal of organic toxic pollutants in to harmless or naturally occurring compounds like carbon dioxide, water, inorganic compounds which are safe for human, animal, plant and aquatic life (Jain and Bajpai, 2012) Bioremediation is involved in degrading, removing, altering, immobilizing, or detoxifying various chemicals and physical wastes from the environment through the action of bacteria, fungi and plants. Microorganisms are involved through their enzymatic pathways act as biocatalysts and facilitate the progress of biochemical reactions that degrade the desired pollutant (Abatenh,

2017). Application of beneficial microbes including free-living microbes, plant growth-promoting rhizobacteria (PGPR), and mycorrhizal fungi as biofertilizers, biopesticides, and biostimulants into field may partially replace the use of agrochemicals leading to increased food production even under biotic and/or abiotic stress conditions (Orozco-Mosqueda *et al.*, 2022; Hartmann and Six, 2023 and Jousset and Lee 2023).

Table 5 Potential biological agents for pesticides

Microorganisms	Compound	Reference
<i>Bacillus, Staphylococcus</i>	Endosulfan	Mohamed, <i>et al.</i> , 2011
<i>Enterobacter</i>	Chlorpyrifos	Niti, <i>et al.</i> , 2013
<i>Pseudomonas putida, Acinetobacter sp., Arthrobacter sp.</i>	Ridomil MZ 68 MG, Fitoraz WP 76, Decis 2.5 EC, malation	Mónica, <i>et al.</i> , 2016 Hussaini, <i>et al.</i> , 2013
<i>Acinetobacter sp., Pseudomonas sp., Enterobacter sp. and Photobacterium sp.</i>	chlorpyrifos and methyl parathion	Ravi <i>et al.</i> , 2015

A number of bacteria decomposers can break down pesticides and pollutants in soil (Hoorman, 2011). Bacteria, those capable of degrading pollutants, usually have central roles in bioremediation, whereas other organisms (e.g. fungi and grazing protozoa) also affect the process (Watanabe, 2001). Fungi have also been described as suitable bioremediation agents to counteract environmental pollution of toxic metals. The ability of fungi to mobilize and translocate molecules and chemical compounds, including toxic metals, between different parts of their mycelium or between their mycelium and plant symbionts makes particularly filamentous fungi interesting organisms for bioremediation applications (Lindahl *et al.*, 2002, Allen *et al.*, 2003, Allen, 2007 and Harms *et al.*, 2011). The algae proved to be effective in hyperaccumulation of heavy metals as well as degradation of xenobiotics (Suresh and Ravishankar 2004). These bioremediation capabilities of microalgae are useful for environmental sustainability (Ellis *et al.*, 2012, Lim *et al.*, 2010). The role of algae *Chlorococcum* spp. and *Scenedesmus* spp. in α -endosulfan degradation was convincingly demonstrated when these algae degraded α -endosulfan to endosulfan sulfate, the major metabolite, and endosulfan ether, a minor metabolite, in a defined liquid medium (Sethunathan *et al.*, 2004). Algae including microalgae and macroalgae can be directly used for soil inoculation without polluting the surrounding environment. They can also reclaim damaged soil, such as desertified soil and saline-alkali land (Wu *et al.*, 2022)

Table 6 The role of soil microorganisms characterized for their potential to reduce/immobilize the heavy metals and other trace elements

Microorganisms	Microbial effects on metals	Reference
<i>Burkholderia capecica</i>	Solubilized CdCO ₃ , ZnCO ₃ and ZnO	Li <i>et al.</i> , 2010
<i>Azotobacter spp.</i>	Immobilized Cr and Cd and decrease their uptake by <i>Triticum aestivum</i> also	Joshi and Juwarkar, 2009
<i>Glomus mosseae</i>	Immobilized Cd, Pb and Cu accumulation. ↑plant fitness and soil fertility	Gonzalez-Chavez <i>et al.</i> , 2004
<i>Rhodococcus specie, Delftia</i>	↓ As (VI) to As (III), ↑plant cell	Yang <i>et al.</i> , 2012

<i>specie, Comamonas specie and Streptomyces lividans specie</i>	enzymatic activities	
<i>Serratia spp.</i>	↓ translocation of Cd, Cu and As from roots to shoots in <i>Lupinus luteus</i>	Aafi <i>et al.</i> , 2012

Biofertilizer production

Biofertilizer is a substance that contains living microorganisms, which, when applied to seed, plant surfaces, or soil, mobilizes the availability of nutrients particularly by their biological activity, and promotes plant growth (Ortiz and Sansinenea, 2021). Biofertilizers add nutrients through the natural processes of fixing atmospheric nitrogen, solubilizing phosphorus, and stimulating plant growth through the synthesis of growth-promoting substances (Wong, 2021 and Ortiz and Sansinenea, 2022). There are different microorganisms that utilize several strategies such as fixing/solubilizing/mobilizing/recycling nutrients in the agricultural ecosystem to be beneficial for the crops, improving plant growth and productivity (Bhowmik and Das 2018). There are many beneficial microorganisms, such as bacteria and fungi, inhabiting the soil and providing suitable conditions for the development of plants (Ortiz, 2021). The beneficial interactions of these microbes with the plants include the nutrients supply to crops, plant growth stimulation, producing phytohormones, biocontrol of phytopathogens, improving soil structure, bioaccumulation of inorganic compounds, and bioremediation of metal-contaminated soils (Sansinenea, 2019). There are several works highlighting the role of beneficial microorganisms in plant grow promotion (Hayat, *et al.*, 2010 and Khan *et al.*, 2020). Moreover, several species of *Bacillus* are able to secrete phytohormones, such as auxins, gibberellins, cytokinins, and abscisic acid, which play different roles in affecting plant cell enlargement and division and enlargement of roots (Poveda and Gonzalez-Andres, 2021)

While *Rhizobium*, *Blue Green Algae* (BGA) and *Azolla* are crop specific, bio-inoculants like *Azotobacter*, *Azospirillum*, Phosphorus Solubilizing Bacteria (PSB), *Vesicular Arbuscular Mycorrhiza* (VAM) could be regarded as broad spectrum biofertilizers (Gupta, 2004 and Mohammadi and Sohrabi, (2012). AMF has a greater potential as a biofertilizer in to improve uptake of nutrients and water, creating plants resistant to soilborne diseases, and helping their host to endure adverse conditions. (Madawala, 2021). Microalgae include eukaryotes such as diatoms and green algae, and prokaryotes such as cyanobacteria, which offer the following advantages as soil biofertilizer (Song, *et al.*, 2022). Currently beneficial microorganisms including PSMs are being applied as biofertilizers for recovering soil fertility and increasing crop production with reduced use of chemical fertilizers (Kumari *et al.*, 2015, Silva *et al.*, 2023, Bittencourt *et al.*, 2024 and Saha *et al.*, 2024).

Table 7 Classification of biofertilizers, mechanism of action, and their examples.

Biofertilizers	Groups	Examples	References
Nitrogen fixing	Free-living	<i>Azotobacter</i> , <i>Anabaena</i> , <i>Clostridium</i> , <i>Aulosira</i> <i>Bejerinkia</i> , <i>Nostoc</i> , <i>Klebsiella</i> , <i>Stigonema</i> , <i>Desulfovibrio</i> , <i>Rhodospirillum</i> , and <i>Rhodopseudomonas</i>	Chaudhury and Kennedy, 2004
	Symbiotic	<i>Rhizobium</i> , <i>Frankia</i> , <i>Anabaena azollae</i> , and <i>Trichodesmium</i>	

	Associative symbiotic	<i>Azospirillum</i> spp., <i>Herbaspirillum</i> spp., <i>Alcaligenes</i> , <i>Enterobacter</i> , <i>Azoarcus</i> spp. <i>Acetobacter diazotrophicus</i>	
Phosphorus solubilizing	Bacteria	<i>Bacillus circulans</i> , <i>B subtilis</i> , <i>Pseudomonas striata</i> , <i>Penicillium</i> spp. <i>B. polymyxa</i> <i>Micrococcus</i> <i>Agrobacterium</i> , <i>Aereobacter</i> and <i>Flavobacterium</i>	Turan, 2006
	Fungi	<i>Penicillium</i> spp., <i>Aspergillus awamori</i> and <i>Trichoderma</i>	
Phosphorus mobilizing	Mycorrhiza	<i>Glomus</i> spp., <i>Gigaspora</i> spp., <i>Acaulospora</i> spp., <i>Scutellospora</i> spp., and <i>Sclerocystis</i> spp.	Chang and Yang 2009
Potassium solubilizing	Bacteria	<i>Bacillus. mucilaginosus</i> , <i>B. circulanscan</i> , <i>B. edaphicus</i> , and <i>Arthrobacter</i> spp.	Etesami, et al., 2017
	Fungi	<i>Aspergillus niger</i> .	
Potassium mobilizing	Bacteria	<i>Bacillus</i> spp.	Jha, 2017
	Fungi	<i>Aspergillus niger</i> .	
Micronutrient	Sulfur oxidizing	<i>Thiobacillus</i> spp.	Itelima, et al., 2018
	Zinc solubilizing	<i>Mycorrhiza</i> , <i>Pseudomonas</i> spp., and <i>Bacillus</i> spp.	Kamran, et al., 2017

Conclusion:

The soil microbes are the dynamic component of soil and performed many beneficial functions in the soil system. Microorganisms are an essential and integral part of living soil influencing various biogeochemical cycles on major nutrients such as carbon, nitrogen, sulphur, phosphorous and other minerals and play superior role in maintaining soil health than other biological component of soil. Beneficial microorganisms play an important role in sustainable agriculture since they maintain the physical, chemical and biological components of soil in an environmentally friendly way. Soil microbes have the diverse roles encompassing soil structural improvement, fascinating soil aggregation, residues decomposition, nutrient cycling, phytohormone production, disease suppression along with bioremediation and biofertilizers. Promoting the diversity and activity of beneficial soil microorganisms is therefore, crucial for maintaining soil quality and supporting long-term agricultural productivity.

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