Open Access Journal of Animal & Plant Husbandry

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Review Article *Volume 4 Issue 1*

The Impact of Beneficial Microorganisms on Soil Vitality: A Review

Mekonen Y*, Abdisa A and Melis B

Department of Soil Resources and Watershed Management, Assosa University, Ethiopia

***Corresponding author:** Mekonen Y, Department of Soil Resources and Watershed Management, College of Agriculture and Natural resource, Assosa University, Ethiopia, Tel: 0910187025, Email: yimammekonen1@gmail.com

Received Date: October 03, 2024; **Published Date:** November 07, 2024

Abstract

The paper summarizes the literature on the critical impact of beneficial microorganisms on soil vitality. Common soil microorganisms, including bacteria, fungi, algae, protozoa, and viruses contribute significantly to enhancing soil fertility through processes such as nitrogen fixation, phosphorus solubilization and mobilization, sulfur cycle, composting, and heavy metal remediation. Their abundance and biomass vary significantly across taxa within the uppermost 15 cm of soil, with bacteria dominating numerically and fungi contributing substantially to biomass. These microorganisms mediate essential biogeochemical cycles in soil, including carbon, nitrogen, and phosphorus cycles, by facilitating the decomposition of organic matter and recycling soil nutrients. Nitrogen-fixing bacteria like Rhizobium are prevalent symbionts capable of biologically fixing nitrogen. Additionally, bacteria such as Micrococcus spp., Enterobacter aerogens, Pseudomonas capacia, fungi including Aspergillus Niger, A. flavus, A. japonicas, Penicillum spp., and actinomycetes like Streptomyces play crucial roles in phosphorus solubilization, making phosphorus available for plant uptake. This synthesis underscores the critical role of beneficial microorganisms in maintaining soil vitality. These organisms interact with plants through beneficial relationships, influencing soil fertility dynamics by enhancing nutrient availability, promoting plant growth, and controlling pathogens. The use of biofertilizers has emerged as a sustainable strategy to improve crop yields and restore soil fertility, reducing environmental impacts linked to chemical fertilizers. Understanding the intricate dynamics of soil-beneficial microorganism and their interactions with Plants are pivotal for optimizing agricultural practices, ensuring long-term soil health, and enhancing productivity in sustainable farming systems.

Keywords: Microorganisms; Soil Fertility; Nitrogen Fixation; Phosphorus Solubilization; Sustainable Agriculture

Introduction

Soil contains millions of organisms in soil fertility improvement and crop production [1]. Soil microorganisms are vital for the preservation of core soil processes linked to strict decomposition, supplement accessibility, and trim yields. Soil physicochemical properties depend on the volume and quality of the soil natural substance, pH, biomass thickness, and imperatives of redox potential [2]. These all have critical impacts on the composition, dynamics, and soil structure of the microscopic culture [3].

The soil, where the interactions between the plant and the environment occur, needs to have enough quality to ensure good development and growth of the plant. There are many beneficial microorganisms, such as bacteria and fungi, inhabiting the soil and providing suitable conditions for the development of plants [4]. "The beneficial interactions of these microbes with the plants include the nutrients supply to crops, plant growth stimulation, producing python hormones, biocontrol of phyto pathogens, improving soil structure, bioaccumulation of inorganic compounds, and bioremediation of metal-contaminated soils [5]. The capacity of soil to supply the essential plant nutrients in available form and a proper balance for healthy plant growth is called soil fertility. Soil fertility depends on the presence of inorganic substances, organic substances, water, and air, as well as, on the presence of microbes [6].

Microorganisms play a very useful role in soil fertility. Usually, people think that microbes are agents of disease, but, they perform many other beneficial functions in soil. The beneficial microorganisms help in the decomposition of organic residues, toxic substances, and other pollutants and add to the soil fertility [7]. The role they play in improving soil fertility has become a subject of more investigations in the recent past.

There are several works highlighting the role of beneficial microorganisms in plant growth promotion [8]. The use of biofertilizers or biopesticides has opened a new way to improve the yield of crops [9]. "Biofertilizers are considered feasible and sustainable attractive biotechnological alternatives to increase crop yield, improve and restore soil fertility, stimulate plant growth, and reduce production costs and the environmental impact associated with chemical fertilization. Biofertilizers have been evaluated in a wide variety of crops, including rice, cucumber, wheat, sugarcane, oats, sunflower, corn, flax, beet, tobacco, tea, coffee, coconut, potato, fan cypress, grass Sudan, eggplant, pepper, peanut, alfalfa, tomato, alder, sorghum, pine, black pepper, strawberries, green soybeans, cotton, beans, lettuce, carrots, and neem, among others" [10]. Microorganisms are the main decomposers and are present in the soil, which has a complex and variable structure and composition. Dynamic changes in soil microecology, mediated by interactions between plant, microbial, and soil communities, have a continuous impact on plant development and soil ecosystem management [11].

Objectives of the Review

- To review types of micro-organisms that plays a role in improving soil fertility.
- To review the role of micro-organisms in improving soil fertility.

Literature Review

Types of Soil Microorganisms

Bacteria: Bacteria are so basic in structure that they are sometimes referred to as bags of enzymes and/or fertilizer-soluble bags [12]. "Nitrogen content (10-30% N, 3 to 10 C: N ratio) in bacteria is higher than most microbes" [13]. Defines "the four main functional groupings of soil bacteria as decomposers, mutualists, pathogens, and lithotrophs".

Nitrogen-Fixing Bacteria: "Microorganisms employed to enhance the availability of nutrients, viz., and nitrogen (by fixing atmosphere N)" [14]. Bacteria commonly referred to as "Rhizobia" are believed to trigger the nodules at the roots of leguminous plants, rarely, and stalk [8]. The distinguished "bacteroid" types help in the fixation of nitrogen from the atmosphere within those nodules and subsequent ammonia is used as a fixed nitrogen supply. "This symbiotic relationship is an exceptional niche for a bacterium and a specialized supply of nitrogen is obtained by the plants" [15]. "Bacteria such as Azotobacter, Azospirillum, Rhizobium, MesoRhizobium, and SinoRhizobium are recognized for enhancing plant growth" [16].

Azospirillum: "Nitrogen fixing Azospirillum species correspond to the optional endophytic diazotrophic classes colonizing the surface and inside of roots, which is globally recognized as bio-nitric nitrogen fixation" [2]. "Azospirillum specifically promotes plants, which boost root and root growth increase the rate of water and mineral intake per root, and maintain soil quality" [17].

Azotobacter: "Azotobacter is a mandatory aerobe, even though at low oxygen concentrations it can develop" [18]. "The ecological spread of this bacterium is dynamic and is linked to different matters that decide whether this bacterium occurs or is absent in a given soil" [19].

Actinomycetes: "Actinomycetes are gram-positive aerobic bacteria that belong to the order Actinomycetes known by their substrate and aerial mycelium production" [20]. "They form associations with some non-leguminous plants and fix N, which is then available to both the host and other plants in the near vicinity" [21]. "Actinomycetes inhabit the rhizosphere of crops, where they increase soil fertility through the recycling of organic matter and solubilizing phosphate" [22].

Cyanobacteria: "Cyanobacteria are photoautotrophic gram-negative bacteria that are plentiful in several soils and take an active part in soil build-up and sustain fertility" [23]. "Cyanobacteria are sustainable sources of the biomass of the solubilized organic matter that is mineralized by soil microorganisms which then, in turn, help farm crop growth" [24].

Rhizobacteria: "Rhizobacteria is the narrowed area of the soil that is specifically influenced by root secretions and related soil microbiomes" [25]. "The physical, chemical, and biological characteristics of the rhizosphere differ significantly from those of the surrounding soil" [26].

Fungi: The fungi residing in soil play a crucial role in its vitality and stability by decomposing organic matter, absorbing toxic metals, and aiding in nutrient cycling [27]. They exhibit resilience to environmental fluctuations and disturbances, contributing significantly to soil preservation and restoration, which ultimately supports plant growth [28]. Fungi demonstrate adaptability to diverse environmental conditions and are influenced by various biotic and abiotic factors, which regulate their diversity and activity [29]. Classified into functional groups, such as biological inspectors and ecosystem regulators, fungi actively participate in the decomposition of organic matter and nutrient transformation, enhancing plant growth through symbiotic relationships like mycorrhizas [30]. Overall, fungi's ability to produce extracellular enzymes enables them to regulate carbon and nutrient balances, highlighting their indispensable role in soil vitality and plant health [31].

Algae: Algae, as a diverse group of simple, primarily autotrophic organisms, contribute significantly to soil vitality and stability. They function as biofertilizers and soil stabilizers, enhancing soil characteristics like carbon content, texture, and aeration. Algal presence in soil results in the emission of growth-promoting substances such as hormones, vitamins, amino acids, and organic acids, which impact various soil organisms. Their primary functions include maintaining soil fertility, particularly in tropical soils, by increasing organic carbon and other organic matter content. Moreover, algae play a crucial role in soil preservation by binding soil particles, reducing erosion, retaining water, controlling nitrates' depletion, and aiding in the weathering of rocks and soil structure formation [32].

Protozoa: Protozoa are single-celled organisms found abundantly in arable soil, with populations ranging from 10,000 to 100,000 per gram. Larger than bacteria, they range from microns to millimeters in size. Protozoa possess a protected dormant stage in their life cycle, enabling them to withstand adverse soil conditions. They primarily derive nutrition from consuming soil bacteria, contributing significantly to maintaining microbial equilibrium in the soil. Certain protozoa have also been harnessed as biological control agents against plant pathogens [33].

Viruses: "Soil viruses are very significant as they can affect soil biology by moving genes from host to host and as a possible source of microbial mortality" [33]. "Consequently, viruses are major players in global cycles, influencing the turnover and concentration of nutrients and gases" [34]. "The field of soil virology is understudied in light of this significance. Studies are carried out on virus diversity and abundance in various geographic zones to investigate the role of viruses in plant health and soil quality. Viruses are extremely common in all environments observed to date, including conditions under which bacterial species of the same ecosystem vary significantly" [2].

Distribution of Microorganisms in Soil

Soil is the most complex habitat that contains a huge abundance of microbial life, which comprises approximately 4-5 × 1030 microbial cells [35]. "It is estimated that 108–109 bacteria, 107–108 viruses, and 105–106 fungal cells are in one gram of soil" [5]. "Soil microbial communities provide ecosystem services such as nutrient recycling, carbon sequestration, water retention, plant growth promotion, and defence" [36]. "The diversity and abundance of microbes are affected by land-use patterns and soil compartments. Two soil compartments can be distinguished based on the strength of their relationship with the plant roots [37].

"The rhizosphere is considered a biological hotspot where plant-microbe, microbe–microbe, and microbe–plant interactions shape microbial community composition. Plant roots secrete organic compounds that support microbial activity [38]. "Rhizosphere soil contains 108–1011 cultivable cells in one gram of soil, which corresponds to approximately 104 microbial species [39]. In addition to plant growth-promoting Rhizobacteria, soil also provides habitats for plant pathogenic microorganisms and opportunistic human pathogenic bacteria [5].

The bulk soil microbial community is an important factor that shapes the rhizosphere microbiome, being the main reservoir from which soil microorganisms are attracted by chemotaxis to root exudates. The same taxa are therefore present in bulk and rhizosphere soils but differ in their relative abundance [40]. Differences in the microbial community between bulk and rhizosphere soils were studied in maize fields by [41]. They observed that the rhizosphere soil microbiota was enriched in Proteobacteria, Bacteroidetes, and Actinobacteria, accounting for 73–80% of total reads versus 46–56% in bulk soil. Rchiad et al. [42] observed that, in a semiarid agroecosystem, although the diversity index of the soil microbiota does not decrease with increasing soil depth, there were differences in the microbial profiles. The abundances of Verrucomicrobia and Bacteroidetes decreased with soil depth. The abundance of soil functional genes was also affected by depth, and most functional categories were observed either in the top layer or at the deepest level [42].

In the uppermost 15 cm of soil, microbial communities exhibit diverse abundance and biomass across different taxa. Bacterial dominate with numbers ranging from 108 to 109 cells per gram of soil, constituting a significant portion of soil microbial biomass which ranges from 40 to 500 g/m2. Fungi, although less abundant in terms of cell numbers (105 to 106 per gram of soil), contribute substantially to soil biomass, ranging from 100 to 1500 g/m2. Algae, Nematodes, and protozoa exhibit lower numerical abundance (102 to 105 cells per gram of soil), with biomass varying widely based on environmental conditions. Actinomycetes, with numbers around 107 to 108 cells per gram of soil, contribute biomass similar to bacteria, ranging from 40 to 500 g/m2. This intricate distribution of microbial species and their biomass highlights their integral roles in soil fertility, nutrient cycling, and overall ecosystem functioning within the upper soil layers.

Microorganisms	**Number/g of soil**	**Biomass (g/m^2)**
Fungi	10^5–10^6	100-1500
Bacteria	10^8-10^9	40-500
Algae	10^4–10^5	Jan-50
Nematodes	10^2–10^3	Varies
Protozoa	10^3–10^4	Varies
Actinomycetes	10^7-10^8	40-500

Table 1: Microbial species' relative abundance and biomass in the uppermost 15 cm of the soil [43].

The Significance of Microorganisms in Enhancing Soil Fertility

Soil fertility refers to the ability of the soil to provide the necessary plant nutrients in an accessible form and the right proportion for the growth of healthy plants. The presence of microorganisms, water, air, and organic and inorganic elements are all necessary for soil fertility [44]. The release of plant nutrients like P, K, and Zn from insoluble inorganic forms, the breakdown of organic residues and the release of nutrients, the creation of beneficial soil humus through the synthesis of new compounds, and the decomposition of organic residues. The production of compounds that promote plant growth, and the improvement of plant nutrition through symbiosis are just a few of the ways that soil microorganisms improve soil fertility [45]. The soil fertility rate is influenced by parameters such as topography, climatic conditions, period, rock form, plants, and microbes, which is why the nature and identity of the microbes in the soil determine the nutrient levels [3].

Nitrogen Fixation: The calculated amount of biologically available nitrogen convertible from the total amount of di nitrogen gas 4 × 109 Tg N to be 473 Tg N [46]. Atmospheric nitrogen is reduced to ammonia (NH3) gas, and this reduction can be made artificially by the Haber–Bosch procedure or occurs naturally as thunderstorms and biological nitrogen fixation, which accounts for 66% of the total fixed N2 [47]. Rhizobium bacteria are symbiotic bacteria linked to leguminous plants. The non-symbiotic or free-living type N2-fixing bacteria are cyanobacteria (blue-green algae, Anabaena) and other species belonging to different genera, such as Azotobacter, Beijerinckia, and Clostridium. Endophytic nitrogen-fixing microorganisms are linked to cereals, grasses, sugarcane, and Azoarcus sp. (rice) [46].

Phosphorus-Solubilizing: Phosphate solubilizing microbes are a group of beneficial microorganisms capable of hydrolyzing organic and inorganic insoluble phosphorus compounds to soluble P forms that can easily be assimilated by plants [48]. Microorganisms solubilize P through the production of low molecular weight organic acids in which hydroxyl and carboxyl groups chelate cations that are associated with complex forms of P (Ca, Al, and Fe) thus rendering phosphate soluble in both basic and acid soils and directly dissolve mineral phosphates from Al-P and Fe-P complexes as a result of anion exchange of PO43- with acid anion [49]. The organic acids and proton release mechanisms by microorganisms also decrease the pH in basic soils and thus solubilize P from the calcium phosphate.

Phosphorus solubilizing microorganisms play a crucial role in enhancing soil fertility and plant nutrition by mobilizing insoluble phosphorus into forms that are accessible to plants [50]. Bacteria such as Enterobacter aerogenes, pseudomonas cepacia, bacillus licheniformis, micrococcus spp., and enterobacter intermedium, along with fungi like Aspergillus flavus, penicillium radicum, Aspergillus Niger, pencillium variable, and Aspergillus japonicas, as well as actinomycetes such as Streptomyces, are known for their ability to produce organic acids, enzymes, and siderophores that can solubilize phosphate minerals [51]. The microorganisms contribute to sustainable agriculture practices by improving phosphorus availability in soils, thereby promoting healthier plant growth and increasing crop yields. Their role underscores the importance of microbial diversity in agro ecosystems and highlights their potential to mitigate phosphorus deficiencies in soils worldwide.

Bacteria	**Fungi**	**Actinomycetes**
Enterobacter aerogenes	*Aspergillus flavus*	
Pseudomonas cepacia	Penicillium radicum	
Bacillus licheniformis	*A. Niger*	Streptomyces
Micrococcus spp.	Penicillium variable	
Enterobacter intermedium	A. Japonicas	

Table 2: Phosphorus solubilizing microorganisms [51].

In a study, scientists showed that Arthrobactersp. Solubilized P about 550 mg/L in their lifetime which is higher than that of Aspergillusniger (400 mg/L), Chryseobacterium sp. (289.8 mg/L), Burkholderia sp. (167.2 mg/L) and Pantoea sp. (479 mg/L).

Phosphorus Mobilization: In the dynamics of soil P, microorganisms are essential for the immobilization and mineralization of organic P. The mineralization of organic P and the solubilization of P from its fixed or precipitated forms, including P from rock phosphate, are two processes that soil microorganisms positively influence [52]. Numerous bacteria assemble P from substrates that are insoluble in minerals and phosphate [53].

Sulfur Cycle: In the soil, organic sulfur is bound as hydrogen sulfide (H_2S). Bacterial species of the genus Thiobacillus changed H_2S to elemental sulfur (S). Inside the phototropic species of the bacterium Chromatium, elemental sulfur crystallizes [54]. Although they emit elemental sulfur into the soil, other Chlorobium and Ectothiorhodospira bacterial species also oxidize hydrogen sulfide. Thiobacillus thiooxidans oxidize elemental sulfur first to sulphite (SO3-), then to sulfuric (H_2SO_4) acid. By adding sulfur to the soil, these bacteria can be cultivated in acidic (pH 2.0 to 3.5) environments and help lower the soil's alkalinity [55]. Eventually, a different bacterial species belonging to the genus Desulfovibrio spp. Converts sulfates to sulphides (H_2S).

Microbial Conversion of Micronutrients

Iron: iron is necessary for plants to produce chlorophyll. The shortage of iron results in young leaves turning chlorotic and is caused by an excess of zinc and manganese in the soil [56]. Iron is found in the form of pyrite, a common iron disulfide that is gradually converted to iron sulfate ($FeSO_4$) by the bacterium Thiobacillus thio oxidans. In the soil, organic iron combines with sugars and basic organic acids to produce complexes. Bacteria of the genus Pseudomonas, Bacillus, Klebsiella, Streptomycetes, and certain filamentous fungus species are known to attack iron that is bound organically [57].

Manganese: The production of chlorophyll depends on manganese and iron. Plants absorb manganese in an ionic form (Mn^{++}). It can be found in plants in two different oxidation states: as divalent and tetravalent manganous ions [58]. Plants absorb the divalent form (Mn^{++}), while microflora is required to transform the tetravalent (Mn^{+4}) form. Bacillus, Azthobacter, Pseudomonas, and Klebsiella are among the bacterial genera that can release ionic manganese from complicated molecules ($MnCO_3$). Although the amount of manganese oxidizers varies from soil to soil, they typically make up 5–15 percent of the soil's total microflora [59].

Microorganisms Serve as Catalysts for Change

The three main categories of microorganisms found in soil are fungi, bacteria, and protozoa. Mineralization is the process by which organic molecules are broken down into their mineral components by bacteria and fungus [60]. Microbes that break down big, complex plant compounds into smaller ones are among the mineralizers. Soil microorganisms do numerous additional critical agricultural tasks. The nitrifying bacteria (Nitro solobus, Nitro bacter, and Nitro somonas) that convert ammonium to nitrate are among the significant groups [61]. Plants can obtain phosphorus more easily thanks to mycorrhizal fungus.

Microbial Participation in the Composting Process

The process of composting involves carefully allowing organic waste or residues to break down to a point where they may be handled, stored, and/or applied to land without harming the environment [62]. It's a method that turns organic materials into humus. Microbial activity is the primary cause of composting by producing a variety of extracellular enzymes, including peptidases, celluloses, hemicelluloses, and pectinases, microbes break down organic molecules [63]. The average yields per hectare for barley, wheat, maize, sorghum, and field pea across treatments with compost are notably higher compared to those without compost application. Specifically, barley yields increased from 1115 kg/ha without compost to 2349 kg/ha with compost, wheat yields rose from 1228 kg/ha to 2494kg/ha, maize yields saw an increase from 1760 kg/ha to 3748 kg/ha, sorghum yields improved from 1338 kg/ha to 2497 kg/ha, and field pea yields increased from 1527kg/ha to 1964 kg/ha [64]. These significant yield enhancements underscore the beneficial impact of compost application on crop productivity, highlighting its role in improving soil fertility, nutrient availability, and overall agricultural sustainability.

The Involvement of Microorganisms in the Removal of Heavy Metals

Microorganisms are essential for eliminating heavy metals that are bad for both human and plant health [65]. By dissolving the links between heavy metals and transforming them into simpler molecules that are safe for both plants and animals, they detoxify heavy metals [66]. By directly absorbing them from the soil, they also eliminate harmful heavy metals.

Enhancing Soil Fertility Through the use of Biofertilizers

Synthetic fertilizers have been used indiscriminately, which have contaminated the soil, contaminated water basins, killed beneficial insects and microorganisms, increased crop disease susceptibility, and decreased soil fertility [67]. Small and marginal farmers are finding this to be unaffordable, and the growing disparity between nutrient supplies and the removal of eroding soil fertility [68]. Additionally, concerns about environmental dangers are growing, and the threat to sustainable agriculture is mounting. In addition to the aforementioned information, long-term applications of biofertilizers over chemical fertilizers are more affordable, environmentally friendly, productive, efficient, and available to marginal and small farmers [69].

Crop	Average yields (kg/ha)	
	Check	Compost
Barley	1115	2349
Wheat	1228	2494
Maize	1760	3748
Sorghum	1338	2497
Field pea	1527	1964

Table 3: Average yields by treatment with compost in kg/ha for 5 crops [64].

Microorganisms	Elements	Uptake (% dry weight)
Citrobacter spp.	Co and Ni	25 and 13
Bacillus spp.	Cd	170
Chlorella vulgaris	Zn and Cu	15 and 14
Rhizopusarrhizus	Au	10
Aspergillusniger	Hg	58

Table 4: Microorganisms and uptake of heavy metals.

Conclusion and Recommendation

From this review, it is noted that soil microorganisms have a tremendous contribution to soil richness, typically achieved through several ways. Organic nitrogen fixation is a financially attractive and environmentally sound route for expanding the supplement supply. The commonly detailed Rhizobium/ legume beneficial interaction contributes significant sums of naturally settled nitrogen to editing frameworks and essentially benefits crops that take after in revolution. Soil microorganisms such as microbes and organisms contribute to plant phosphorus nourishment through the solubilization of settled or accelerated phosphorus from complexes with Al and Fe in acidic soils and calcium complexes in alkaline soils. Phosphate solubilizing rhizosphere microscopic organisms incorporates a high potential to be utilized within the management of P-deficient soils. Additionally, soil microscopic organisms improve soil structure and organic matter content, strengthen stress resistance, stabilize soil totals, and help with the solubilization of mineral phosphates and other supplements. More soil natural N and other supplements are held by soil microbes within the plant-soil framework, which brings down the request for fertilizer N and P and makes strides in nutrient release.

Generally, I organized this review from diverse researcher discoveries and I suggested that Soil microorganisms play a significant part in improving soil fertility and trim generation so, it is way better to make an appropriate environment for organisms to do their activities.

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 manuscripts.

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