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Microbial mediation of nutrient cycling: Nitrogen, phosphorus, and micronutrients

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Abstract
Microbial mediation is an essential part of the nutrient cycling in the soil and water ecosystem, and it has a direct effect on the soil fertility, plant productivity, and sustainability of ecosystems. The bacteria, fungi, actinomycetes, and archaea are important in the transformation and mobilization of essential nutrients such as nitrogen, phosphorus, and micronutrients (e.g., iron, zinc, and manganese) to be absorbed by plants. Nitrogen fixation, nitrification, and denitrification are among the processes involved in the nitrogen cycle, and they are regulated by specialized microbial communities that maintain the balance of different forms of nitrogen. On the same note, phosphate-solubilizing microorganisms (PSMs) increase phosphorus availability by releasing organic acids and enzymes through which organic acids solubilize insoluble phosphates. In addition, microbes play a role in the release of micronutrients by siderophore release, redox reaction, and chelation processes, and enhance the nutrition and health of plants and soil. Such microbial processes not only maintain a nutrient turnover, but also reduce losses of nutrients and environmental pollution. Knowledge of microbial-based nutrient changes can give prospects to come up with biofertilizers and sustainable nutrient management strategies that can lessen reliance on chemical fertilizers. The paper identifies the process, ecological roles, and uses of microbial mediation in the cycling of nitrogen, phosphorus, and the micronutrients, with a focus on their role in sustainable agriculture and protection of the environment.

Keywords: Microbial mediation, nutrient cycling, nitrogen fixation, phosphate solubilization, micronutrients, biofertilizers, soil fertility, sustainable agriculture

Introduction
Microorganisms are the invisible engineers of nutrient cycling, and they coordinate the transformation and mobilization of vital elements like nitrogen, phosphorus, and even micronutrients in the earth and water systems. Their metabolic processes are fundamental to soil fertility, plant productivity, and ecosystem resilience and can therefore not be ignored by the natural and managed environment. Nitrogen fixation, nitrification, and denitrification processes catalyzed by the soil microbiota constitute the components of the nitrogen cycle, which transforms atmospheric nitrogen into bioavailable forms and regulates the flux of nitrogenous compounds, which is of significant importance to plant growth and the determination of greenhouse gases and water quality. These changes are mediated by a set of microbial enzymes, including nitrate reductases, ureases, the activities of which are sensitive to environmental conditions, such as temperature, moisture, pH, and substrate availability, which, in turn, can be further controlled by man-made activities and climate change (Daunoras *et al*., 2024; Deb *et al*., 2024) [20, 21]. The other important macronutrient, phosphorus, is usually found in soils, yet not easily available to plants due to the form in which it appears. In this case, phosphate-solubilising microorganisms (PSMs) take a central stage by releasing organic acids and phosphatases, mobilising inorganic phosphorus and organic phosphorus, and improving their bioavailability and eliminating the requirement of chemical fertilisers (Tian *et al*., 2021; Silva *et al*., 2023; Timofeeva *et al*., 2022) [59, 51, 60]. Stoichiometric ratios of carbon, nitrogen, and phosphorus in the biomass of microbes also regulate the transformation and availability of phosphorus, and the C: N:P ratios of soil and the microbial biomass affect the efficiency of transformations and their availability (Chen *et al*., 2023) [13]. In addition to nitrogen and phosphorus, the microbes are also part of the micronutrient cycling of iron, zinc, and manganese, the solubility of which and uptake are directly influenced by microbes through the production of siderophores and redox

conversion, directly affecting the well-being and productivity of plants (Timofeeva *et al*., 2023) [61]. The cycling of these nutrients is closely linked, and the microbial communities respond dynamically to changes in nutrient inputs, land management, and environmental conditions. The nutrient imbalance and the decline of soil fertility and environmental degradation can be caused by disruption of microbial-mediated nutrient cycling, which can occur due to the excessive usage of fertilisers, pollution, or climate change (Daunoras *et al*., 2024; Luo *et al*., 2022) [20, 37]. The harnessing and understanding of microbial processes is therefore the focus of sustainable agriculture, the aftermath of environmental effects, and food security. The more it is revealed about what microbial communities are, and how they operate, the more apparent it is that microbes are the invisible engineers of nutrient cycling, and moderate the availability and transformation of essential elements and the productivity and sustainability of ecosystems (Daunoras *et al*., 2024; Tian *et al*., 2021; Silva *et al*., 2023; Timofeeva *et al*., 2023; Chen *et al*., 2023; Timofeeva *et al*., 2022; Deb *et al*., 2024) [20, 59, 51, 61, 13, 60, 21].

Microbial Mediation in the Nitrogen Cycle

Nitrogen cycle Microbial mediation plays a key role in the nitrogen cycle, and it coordinates the conversion of nitrogen via a multifaceted network of biochemical pathways that can maintain ecosystem productivity and environmental health. The nitrogen cycle includes a number of the most important microbially mediated processes: nitrogen fixation, ammonification, nitrification, denitrification, anammox anaerobic ammonium oxidation, and dissimilatory nitrate reduction to ammonium (DNRA). Diazotrophic bacteria and archaea fix nitrogen from the atmosphere in the form of dinitrogen (N_2) of the atmosphere to ammonia (NH_3) and make it available to other living organisms and plants (Figure 1). This is catalyzed by the enzyme nitrogenase, which is available in multiple isoforms with the canonical molybdenum-dependent form, and alternative forms based on vanadium or iron, thus adapting to the different conditions of the environment (Bellenger *et al*., 2020) [10]. After it has been fixed, plant and animal residues contain organic nitrogen that is mineralized by heterotrophic microbes under ammonification to release ammonium (NH_4^+) into the soil. Ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) are specialized groups of microorganisms that mediate the two-step aerobic process of nitrification, in which NH_4^+ is first reduced to nitrite (NO_2^-) and then further oxidized to nitrate (NO_3^-) (Hayatsu *et al*., 2021; Ni *et al*., 2023; Mai *et al*., 2021) [30, 40, 38]. The nitrification activity of two organisms, which has been the prevailing perspective on the process of nitrification, has been called into question by the recent identification of complete ammonia-oxidizing (comammox) bacteria, including some Nitrospira species, which can execute the entire process of converting ammonia to nitrate by themselves (Hayatsu *et al*., 2021; Ni *et al*., 2023) [30, 40]. Nitrification is the process that is extremely sensitive to the environmental factors of pH, oxygen, and substrate concentration and is a key process in agricultural soils that helps to affect the nitrogen loss, pollution of groundwater, and the formation of greenhouse gases, in particular, nitrous oxide (N_2O) (Hayatsu *et al*., 2021; Ni *et al*., 2023; Beeckman *et al*., 2023) [30, 40, 9]. The process of denitrification, which involves the reduction of nitrate to dinitrogen gas (N_2) in stages, is carried out under the conditions of low oxygen by the facultative anaerobic bacteria, when nitrate serves as the electron acceptor and intermediates are produced; nitrite, nitric oxide (NO), and N_2O (Mai *et al*., 2021; Klimasmith and Kent, 2022) [38, 32]. This is essential to seal the nitrogen cycle and reduce the buildup of reactive nitrogen in the environment, although the partial process of denitrification results in a substantial flow of N_2O, a powerful greenhouse gas (Ni *et al*., 2023; Beeckman *et al*., 2023; Klimasmith and Kent, 2022) [40, 9, 32]. The oxidation of ammonium under conditions of anaerobic conditions is catalyzed by anammox bacteria, which were found in both natural and artificial environments, converting ammonium to N_2 in the presence of nitrite in the environment (this form of oxidation is commonly called the anaerobic oxidation of ammonium), and is among the primary mechanisms of nitrogen loss in the aquatic environment and some terrestrial ecosystems (Mai *et al*., 2021; Harb *et al*., 2021) [38, 29].

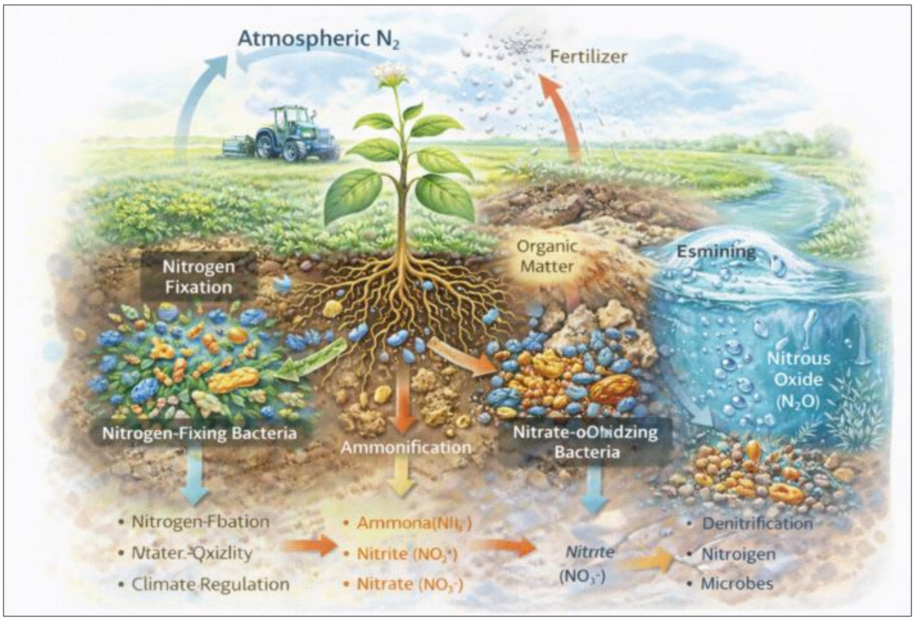

Fig 1: Microbial Mediation in the Nitrogen Cycle

Another anaerobic process is DNRA, which changes nitrate to ammonium and keeps nitrogen in the ecosystem, causing a change in the balance between the loss and retention of nitrogen (Klimasmith and Kent, 2022) [32]. These microbial communities are diverse and active and depend on soil characteristics, plant-microbe interactions, and fertilization regimes, and are further changed by the presence of plant root exudates and allelopathic compounds, which determine the populations and activities of ammonia oxidizers (Chinthalapudi *et al*., 2025) [16]. In agrocosm, the balance in the microbial processes is broken by excessive nitrogen fertilization, which tends to increase nitrification and denitrification rates and results in high levels of nitrate leaching and emissions of N_2O (Beeckman *et al*., 2023; Chinthalapudi *et al*., 2025) [9, 16]. Nitrogen usage efficiency and minimizing adverse effects on the environment are being investigated by the use of nitrification inhibitors, biological inhibitions of nitrification by plants, and the application of microbial inoculants (Beeckman *et al*., 2023; Klimasmith and Kent, 2022; Chinthalapudi *et al*., 2025) [9, 32, 16]. In addition, the recent discoveries of specific innovations like heterotrophic nitrification-aerobic denitrification (HNAD), Fe (III)-mediated anaerobic ammonium oxidation (Feammox), and denitrifying anaerobic methane oxidation (DAMO) have contributed to expanding the knowledge of nitrogen conversion and provide new opportunities to treat wastewater and reduce nitrogen levels in the environment. Microbial community structure, abundance of functional genes, and environmental parameters interactivity make it clear that nitrogen cycling is a complex process, and merging metagenomics, isotopic tracing, and process-based modeling are necessary to provide answers to the mechanistic basis of microbial nitrogen transformations (Deb *et al*., 2024; Chinthalapudi *et al*., 2025) [21, 16].

Microbial Role in the Phosphorus Cycle

Microorganisms have a central role in the phosphorus (P) cycle and are important agents in converting soil P, which exists in unavailable forms, into bioavailable nutrients that are necessary in plant growth and ecosystem production. Although soils may have a lot of total P, a majority of it is present in unavailable insoluble mineral and organic complexes that cannot be directly utilized by plants. This limitation is overcome by employing several techniques of biochemical mobilization and mineralization of P by phosphate-solubilizing microorganisms (PSMs) such as bacteria, fungi, and actinobacteria (Table 1), which include a range of biochemical mechanisms to address this limitation. These bacteria release organic acids (gluconic, citric, and oxalic acids) that bind cations to phosphate, reducing the pH, and dissolving mineral phosphates to plant-available orthophosphate. Besides, PSMs generate phosphatase enzymes (e.g., alkaline and acid phosphatases, phytases), breaking down organic P compounds to inorganic phosphate (Ughamba *et al*., 2025; Fu *et al*., 2024) [62, 27]. In many bacteria, expression of the genes of phosphate uptake and solubilization is regulated by the Pho regulatory system, which enables microbes to respond to changing P availability (Timofeeva *et al*., 2022; Ughamba *et al*., 2025) [60, 62]. Fungi (especially Penicillium and Aspergillus genera) can also solubilize inorganic and organic P, and sometimes can synergistically stimulate the further transfer of the nutrient by bacteria and mycorrhizal fungi (Fu *et al*., 2024; Etesami *et al*., 2021) [27, 24]. The functioning and the abundance of PSMs depend on the characteristics of soil, the exudates of plant roots, the methods of fertilization, and stress factors of the environment (salinity or nitrogen loading) that can alter the composition of the microbial community and the abundance of functional genes (Luo *et al*., 2022; Chen *et al*., 2023; Etesami *et al*., 2021; Dey *et al*., 2021) [37, 13, 24, 22]. The use of PSMs as biofertilizers in agricultural systems is becoming an established sustainable option to chemical P fertilizer, as it has been noticed to positively affect soil fertility, environmental impact, and crop yields (Tian *et al*., 2021; Silva *et al*., 2023; Ughamba *et al*., 2025; Liu *et al*., 2023; Bargaz *et al*., 2021; Castagno *et al*., 2021) [59, 51, 62, 36, 8, 12]. Nevertheless, applying laboratory successes to the field is still difficult because of the fluctuating soil conditions, interference with native micro-organisms, and uneven recapitulation in different environmental conditions (Ughamba *et al*., 2025) [62]. Combining and co-culturing PSMs with other growth-promoting microorganisms of plants, including nitrogen-fixers and mycorrhizal fungi, and synthetic microbial communities has potential in enhancing P cycling and use in natural and managed ecosystems (Zhu *et al*., 2024; Bargaz *et al*., 2021; Etesami *et al*., 2021) [72, 8, 24]. It is also important to understand the stoichiometrical relationships between carbon, nitrogen, and phosphorus in the soil and in the microbial biomass since those ratios control the activity of microbial enzymes and the effectiveness of P transformation processes (Chen *et al*., 2023) [13]. Finally, to ensure sustainable agriculture, environmental conservation, and food security in the world, it is necessary to utilize the full capabilities of microbial mediation in the phosphorus cycle.

Table 1: Key Microbial Mechanisms in the Phosphorus Cycle

Mechanism/Process	Microbial Group(s)	Function/Outcome	Citations
Organic acid secretion	Bacteria, Fungi	Solubilizes mineral phosphates, increases P availability	(Tian *et al*., 2021; Silva *et al*., 2023; Ughamba *et al*., 2025; Fu *et al*., 2024) [59, 51, 62, 27]
Phosphatase enzyme production	Bacteria, Fungi, Actinobacteria	Mineralizes organic P, releases inorganic phosphate	(Ughamba *et al*., 2025; Fu *et al*., 2024; Bargaz *et al*., 2021) [62, 27, 8]
Pho regulon activation	Bacteria	Regulates P uptake and solubilization genes	(Timofeeva *et al*., 2022; Ughamba *et al*., 2025) [60, 62]
Mycorrhizal associations	Fungi (AMF), Bacteria	Enhances P uptake via symbiosis	(Fu *et al*., 2024; Etesami *et al*., 2021) [27, 24]
Synergistic microbial interactions	Bacteria, Fungi, AMF	Improves P cycling and plant growth	(Zhu *et al*., 2024; Bargaz *et al*., 2021; Etesami *et al*., 2021) [72, 8, 24]
Adaptation to environmental stress	PSMs, PSB, PSF	Maintains P solubilization under salinity, N loading	(Luo *et al*., 2022; Etesami *et al*., 2021; Dey *et al*., 2021) [37, 24, 22]

Microbial Mediation of Micronutrients

The microorganisms play a crucial role in the cycling and bioavailability of micronutrients, including iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), and sulfur (S), which are necessary in the growth of plants, the crop yield, and human food (Figure 2). These micronutrients in soils are often not readily accessible to plants and therefore become prone to deficiencies, which affect agricultural productivity and health issues globally, especially about hidden hunger attributed to a nutrient-poor diet (Singh and Prasanna, 2020) [52]. A complex of biochemical mechanisms is used by microbial communities, bacteria, actinobacteria, and fungi to mobilize, solubilize, and transport micronutrients in the rhizosphere. To illustrate, the interstitial microorganisms release organic acid and phenolic acids that acidify the rhizosphere, chelate metal ions, and thus enhance the plant availability of Fe and Zn (Singh and Prasanna, 2020) [52]. Especially important are siderophore-producing bacteria and fungi that bind Fe (III) with high affinity and are crucial in the uptake of Fe (III) by the microbes and plants (Timofeeva *et al*., 2023) [61].

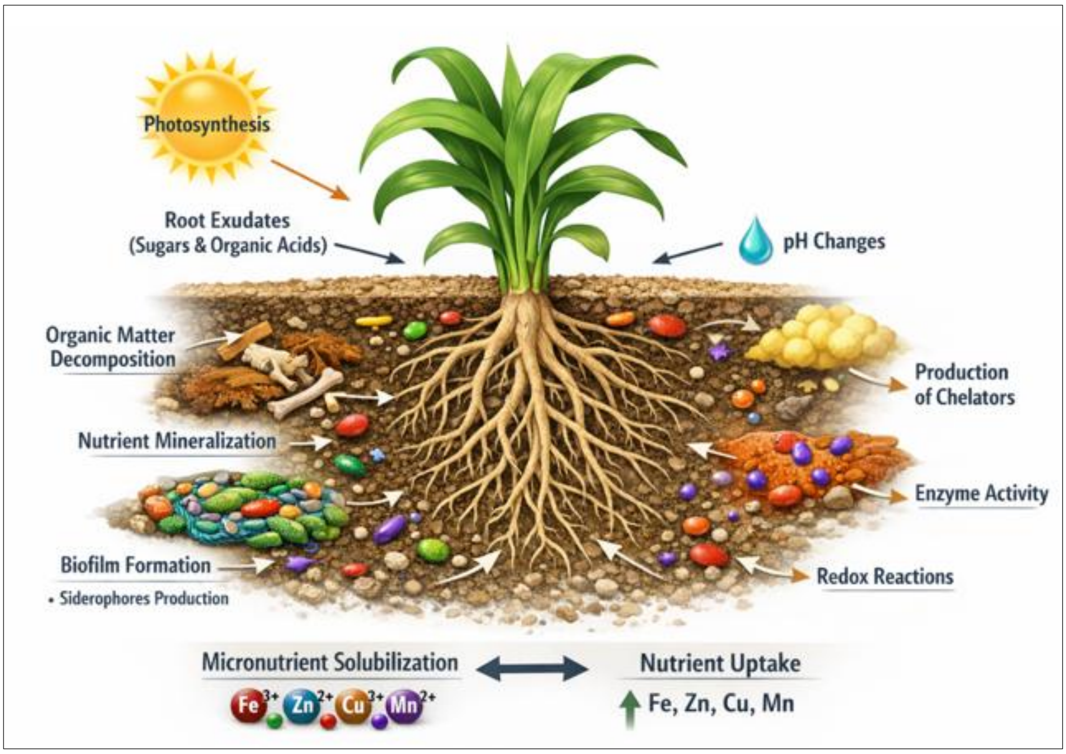

Fig 2: Microbial Mediation of Micronutrients

Moreover, some microbes may decrease the amount of phytic acids in grains, which otherwise complex micronutrients and restrict their bioavailability in human diets, thereby improving the nutritional value of food crops (Singh and Prasanna, 2020) [52]. Plant root interactions with microbes may also cause morphological alterations, including enhanced root surface area and architecture, which also enhances micronutrient uptake (Singh & Prasanna, 2020) [52]. It has also been shown that plant Zn and Fe transporter genes are upregulated upon colonization by microbes, which directly affects plant nutrient acquisition pathways (Singh and Prasanna, 2020) [52]. In addition to Fe and Zn, other micronutrients are also subjected to cycling by the microbes: an example of this is Bacillus species that can increase the nutritional status of plants in the form of sulfur by releasing volatile organic compounds such as dimethyl disulfide, which plants can better absorb than inorganic sulfate (Singh *et al*., 2022) [53]. The interaction of plant roots, soil microbiota, and environmental conditions defines plant rhizosphere microbiome composition and functionality, and nutrient-dependent signaling and competitiveness can determine the success and performance of particular microbial taxa in mediating micronutrient cycling (Singh *et al*., 2022) [53]. In the field of sustainable agriculture, the use of microbial inoculants, including seed priming by useful bacteria or fungi, has potential as a biofortification strategy to enhance the quantity of micronutrients in food grains without depending on the use of chemical fertilizers (Singh and Prasanna, 2020) [52]. Significant microbial genes and proteins that mediate micronutrient translocation are being determined and engineered using modern tools such as transcriptomics and metaproteomics, and will be used to streamline plant-microbe interactions to increase nutrient uptake (Singh & Prasanna, 2020) [52]. The success of microbial biofortification strategies, however, may be different by soil type, crop species, and environmental conditions, and integrated and site-specific strategies are required. Finally, micronutrient mediation by microbes forms a basis of soil fertility, plant nutrition, and human health, and its application in agricultural systems is the key to curbing micronutrient deficiencies and achieving sustainable food systems (Singh and Prasanna, 2020; Singh *et al*., 2022; Timofeeva *et al*., 2023) [52, 53, 61].

Interactions between Microbial Communities and Nutrient Cycles

The microbial communities are the primary architects of the nutrient cycle; they promote the transformation, mobilization, and stabilization of essential components, including carbon (C), nitrogen (N), and phosphorus (P), in a variety of ecosystems. These are communities of bacteria, fungi, archaea, and protists that interact through complex networks, enhancing the soils, plant performance, and ecosystem stability (Daunoras *et al*., 2024; Dai *et al*., 2021; Duan *et al*., 2024; Wu *et al*., 2023; Albornoz *et al*., 2022) [20, 19, 23, 65, 1]. The organic matter is broken down and the nutrients transformed into bioavailable forms by the action of microbial enzymes, such as glucosidases, phosphatases, and ureases, which directly affect the rate of C, N, and P cycling (Daunoras *et al*., 2024; Dai *et al*., 2021) [20, 19]. The environment (i.e., temperature, moisture, pH), land management processes, as well as biotic interactions (i.e., competition, cooperation, syntrophy) determine the structure and functioning of microbial communities (Daunoras *et al*., 2024; Dai *et al*., 2021; Albornoz *et al*., 2022) [20, 19, 1] (Table 2). As an illustration, in the plant-soil system, arbuscular mycorrhizal fungi (AMF) and their accompanying bacteria create a continuum enabling the transfer of carbon by plants in exchange for soil mineral nutrients, where AMF-bacteria interactions increase the cycling of N and P (Duan *et al*., 2024) [23]. Consortia of bacteria and microalgae can synergistically eliminate wastewater nutrients in aquatic systems and engineered systems, with the microalgae supplying oxygen to bacteria in the nitrification of wastewater and the bacteria supplying inorganic carbon to the growth of the microalgae (Fallahi *et al*., 2021) [25]. New amendments, including biochar, can also help to regulate microbial community structure and nutrient cycling mechanisms by changing the properties of the soil and offering new ecological habitats (Dai *et al*., 2021) [19]. C, N, P interactions appear to be particularly pronounced in the microbial biomass stoichiometry, where the nutrients become available to cause compensatory alteration in microbial metabolism and community structure, impacting the nutrient cycling of other nutrients (Dai *et al*., 2021; Luo *et al*., 2022) [19, 37]. The interactions among the communities of microbes and nutrient cycles are therefore fundamental to predicting the changes of the ecosystems in response to global changes, to enhanced sustainable agriculture, and to environmental impacts.

Table 2: Examples of Microbial Interactions and Their Effects on Nutrient Cycles

Microbial Interaction Type	Nutrient Cycle(s) Affected	Mechanism/Outcome	Citations
Enzyme-mediated decomposition	C, N, P	Breakdown of organic matter, release of nutrients	(Daunoras *et al*., 2024; Dai *et al*., 2021; Wu *et al*., 2023) [20, 19, 65]
Mycorrhizal-bacterial cooperation	N, P	Enhanced nutrient exchange and plant uptake	(Duan *et al*., 2024; Albornoz *et al*., 2022) [23, 1]
Microalgae-bacteria consortia	N, P	Synergistic nutrient removal in wastewater, oxygen, and metabolite exchange	(Fallahi *et al*., 2021) [25]
Biochar-induced community shifts	C, N, P	Altered microbial diversity, coupled with nutrient transformations	(Dai *et al*., 2021) [19]
Competition and facilitation	C, N, P	Niche differentiation, resource partitioning, or mutualistic nutrient exchange	(Albornoz *et al*., 2022; Zhu *et al*., 2024) [1, 72]
Environmental disturbance response	C, N, P	Changes in enzyme activity, community structure, and nutrient cycling efficiency	(Daunoras *et al*., 2024; Aralappanavar *et al*., 2024; Wu *et al*., 2023) [20, 5, 65]

Applications in Sustainable Agriculture

Sustainable agriculture is a wide term to describe a wide range of practices and technologies aimed at satisfying the present needs in food production without compromising the resources and the environmental well-being of future generations. The most prominent ones are climate-smart agriculture (CSA), precision farming, integrated crop-livestock systems, circular agriculture, and the implementation of more advanced digital technologies, the Internet of Things (IoT), artificial intelligence (AI), and quantum computing. CSA methods, such as zero/minimum tillage, crop rotation, organic manuring, reduced residue retention, agroforestry, reduce farm resilience to climate change, boost farm yields, and enhance economic diversification, and reduce greenhouse gas emissions and support the United Nations Sustainable Development Goals (Wanglin and Rahut, 2024; Coulibaly *et al*., 2021; Sithole and Olorunfemi, 2024) (Figure 3). Precision agriculture utilizes the IoT, remote sensing, and smart irrigation to optimize water and nutrient application and reduce environmental impact, and allows real-time monitoring, which is particularly important in arid and resource-limited areas (Khan *et al*., 2021; Xing and Wang, 2024; Shahab *et al*., 2024; Xing and Wang, 2024; Kumar *et al*., 2024) [31, 67, 48, 67, 33]. Circular agriculture and integrated crop-livestock-forestry systems can close nutrient and energy cycling, enhance soil health, increase productivity, and decrease the use of synthetic fertilizers, as is the case in Brazilian Cerrado and tropical commercial farms (Oliveira *et al*., 2024; Moreira *et al*., 2023; Garrett *et al*., 2020) [41, 39, 28].

Fig 3: Applications in Sustainable Agriculture

Urban and peri-urban agriculture, enabled by technological advances, is a solution to food security and environmental issues in metropolitan regions as it makes the most of space, recycles, and minimizes food miles (Fei *et al*., 2025) [26]. Climate-independent hydroponics and other soilless systems conserve water and land and are highly productive (Rajendran *et al*., 2024) [43]. Nevertheless, these developments have challenges, including knowledge gaps, insufficient access to finance, land tenure insecurity, and the need to support with supportive policies and education (Wanglin *et al*., 2024; Siebrecht, 2020; Kuyah *et al*., 2021; Sithole and Olorunfemi, 2024). These barriers can only be overcome through international cooperation, capacity building, and incorporation of the social, economic, and environmental aspects in the policy frameworks. The bottom line is that the multi-faceted use of sustainable agricultural practices that combine both the conventional and the technological innovation is critical to the provision of food security, environmental conservation, and rural livelihoods in a dynamic world.

Environmental Implications of Microbial Nutrient Cycling

The cycling of nutrients by microbes is a primary process in the work of the ecosystem, which supports the fertility of the soil, the growth of plants, and the balance of greenhouse gases. The microorganisms mediate the conversion and mobility of essential nutrients, including carbon (C) nitrogen (N) and phosphorus (P), by means of a complex of metabolic pathways and ecological reactions, which have a direct effect on the soil health, water quality, and the atmosphere (Wu *et al*., 2023; Daunoras *et al*., 2024) [65, 20] (Table 3). Carbon cycling is caused by the degradation of organic matter by microbes in soil and makes the organic carbon stable, influencing the soil carbon storage, which is essential in mitigating climate change (Wu *et al*., 2023; Tariq *et al*., 2024) [65, 58]. Nitrogen cycling, organized by various microbial guilds, refers to nitrogen fixation, nitrification, denitrification, and anammox, all of which balance the supply of reactive nitrogen to the plants and the release of nitrous oxide (N_2O), a strong greenhouse gas (Yang *et al*., 2021; Zhou *et al*., 2024; Daunoras *et al*., 2024; Opande *et al*., 2025) [69, 71, 20, 42]. Similarly, due to its solubility by microbes and its mineralization, phosphorus cycling increases plant-available P and allows crop growth (Dai *et al*., 2021; Daunoras *et al*., 2024) [19, 20]. Nevertheless, the introduction of microplastics, antibiotics, heavy metals, and other anthropogenic influences can alter microbial communities and enzymatic functions, disrupting nutrient cycling, causing soil to lose its fertility, and posing a risk to the environment, e.g., eutrophication and greenhouse gas emissions (Aralappanavar *et al*., 2024; Zhou *et al*., 2024; Salam *et al*., 2023; Opande *et al*., 2025) [5, 71, 46, 42]. As an example, microplastics and the related contaminants can alter microbial diversities, enhance microbial diversity that degrades plastics and recycles nutrients, and enhance N_2O bioavailability, yet they can also increase N_2O emission and nitrification disturbances (Aralappanavar *et al*., 2024; Salam *et al*., 2024; Salam *et al*., 2023) [5, 45, 46]. Environmental antibiotics may suppress or enhance important nitrogen cycling pathways, usually leading to reduced nitrogen loss and increased N_2O emission (Zhou *et al*., 2024) [71]. The heavy metals are harmful to the microbial-mediated N transformations and pose a threat to soil stability and productivity (Opande *et al*., 2025) [42]. On the other hand, useful interventions include biochar additions, microbial inoculants, and utilization of plant-microbe relationships, which can increase the cycling of nutrients, improve soil structure, and attain sustainable agriculture (Dai *et al*., 2021; Yusuf *et al*., 2025; Shahwar *et al*., 2023; Boubekri *et al*., 2022) [19, 70, 49, 11]. Biochar, e.g., alters the pH of soil and supplies nutrients that are labile, thus triggering microbial activity and nutrient cycling, yet the effects are dependent on biochar type and environmental conditions (Dai *et al*., 2021) [19]. Rhizobacteria and endophytes that promote plant growth are eco-friendly substitutes for chemical fertilizers, promoting nutrient uptake, stress resistance, and bioremediation (Baloch *et al*., 2024; Anand *et al*., 2023; Yusuf *et al*., 2025; Shahwar *et al*., 2023; Boubekri *et al*., 2022) [7, 4, 70, 49, 11]. The multifunctionality and resilience of microbial communities are therefore key to the restoration of ecosystems, climate control, and sustainable food production (Albornoz *et al*., 2022; Coban *et al*., 2022; Yusuf *et al*., 2025; Boubekri *et al*., 2022) [1, 17, 70, 11]. However, interactions between microbes and their environments and emerging contaminants and climate change suggest that interdisciplinary research is both necessary and beneficial to protect and maximize microbial nutrient cycling to ensure environmental sustainability (Albornoz *et al*., 2022; Coban *et al*., 2022; Daunoras *et al*., 2024; Tariq *et al*., 2024) [1, 17, 20, 58].

Table 3: Environmental Impacts of Microbial Nutrient Cycling: Key Aspects

Aspect/Driver	Environmental Implication	Citations
Carbon Cycling	Stabilizes soil organic carbon, mitigates climate change, and supports soil fertility.	(Wu *et al*., 2023; Tariq *et al*., 2024) [65, 58]
Nitrogen Cycling	Regulates plant N availability, influences N_2O emissions, and affects water quality	(Yang *et al*., 2021; Zhou *et al*., 2024; Daunoras *et al*., 2024; Opande *et al*., 2025) [69, 71, 20, 42]
Phosphorus Cycling	Enhances P availability, supports crop growth, reduces P leaching	(Dai *et al*., 2021; Daunoras *et al*., 2024) [19, 20]
Microplastics	Alters microbial diversity, increases N/P bioavailability, may raise N_2O emissions	(Aralappanavar *et al*., 2024; Salam *et al*., 2024; Salam *et al*., 2023) [5, 45, 46]
Antibiotics	Inhibit/stimulate N cycling, increase N_2O emissions, disrupt microbial communities.	(Zhou *et al*., 2024) [71]
Heavy Metals	Impair N transformations, threaten soil fertility and stability	(Opande *et al*., 2025) [42]
Biochar Amendments	Enhance microbial activity, nutrient cycling, and soil structure	(Dai *et al*., 2021) [19]
Microbial Inoculants	Improve nutrient acquisition, reduce chemical fertilizer use, and promote sustainability.	(Yusuf *et al*., 2025; Shahwar *et al*., 2023; Boubekri *et al*., 2022) [70, 49, 11]
Plant-Microbe Interactions	Boost resilience, nutrient cycling, and bioremediation	(Baloch *et al*., 2024; Anand *et al*., 2023; Yusuf *et al*., 2025; Boubekri *et al*., 2022) [7, 4, 70, 11]
Climate Change	Alters enzyme activity, microbial community structure, and nutrient cycling rates	(Daunoras *et al*., 2024; Tariq *et al*., 2024) [20, 58]

Future Prospects and Research Directions

Sustainable agriculture is becoming more and more closely linked with developments in microbial science, biotechnology, and systems-level knowledge of the interactions of plants, microbes, and soil. With an increase in the world food demand and environmental pressures, studies are moving to develop beneficial microbes, including microalgae, actinobacteria, endophytes, and plant growth-promoting rhizobacteria (PGPR), to boost crop productivity, nutrient cycling, and resilience to both biotic and abiotic stresses (Alvarez *et al*., 2021; Boubekri *et al*., 2022; Anand *et al*., 2023; Kumawat *et al*., 2021; Shahwar *et al*., 2023; Chen *et al*., 2024) [3, 11, 4, 34, 49, 15] (Table 4). Development of microbial consortia and synthetic communities (SynComs) to match particular crops and the environment, the use of omics technologies (metagenomics, metabolomics, transcriptomics) to dissect multifaceted interactions between plants and microbes, and engineering of the rhizosphere microbiome to acquire nutrients, reduce disease, and survive stress are only a few of the key areas of research (Zuluaga *et al*., 2024; Baloch *et al*., 2024; Yusuf *et al*., 2025; Rajguru *et al*., 2024) [73, 7, 70, 44]. There is an increasing interest in the working of microalgae and cyanobacteria as renewable biofertilizers and biostimulants, and future research is required to maximize the production of inoculum, its application techniques, and performance in various soils and agroecological regions (Alvarez *et al*., 2021) [3]. In the same manner, the multifunctional applications in nutrient mobilization, biocontrol, and phytoremediation by actinobacteria and endophytes are under development, and synthetic biology and nanotechnology are likely to enhance the industrial production of bioinoculants (Boubekri *et al*., 2022; Anand *et al*., 2023; Ayilara *et al*., 2022) [11, 4, 6]. Phosphorus-solubilizing microorganisms and microbial metabolites have potential opportunities to decrease the use of chemical fertilizers and increase the efficiency of nutrient use, although more research is needed to identify new strains, understand the solubilization process, and create strong bioformulations to work in the field (Silva *et al*., 2023; Chen *et al*., 2024) [51, 15]. Regardless of these developments, there is still a challenge in the translation of laboratory achievements into the field-scale application, as there are differences in the soil types, climate, and management methods of crops. Trials of biofertilizer, quality control, and education of farmers must be standardized so that the performance is uniform and acceptable to many farmers (Zuluaga *et al*., 2024; Samantararay *et al*., 2024). The long-term effects of microbial amendments on the health of the soil, the diversity of microorganisms, and ecosystems, and the interactions among microbial necromass, soil organic matter, and microbial nutrient cycling under different climate conditions are also the subjects of future investigation (Wu *et al*., 2023; Al-Shammary *et al*., 2024; Chen *et al*., 2024) [65, 2, 15]. Measuring the contribution of microbes to carbon sequestration of soils and nutrient turnover and plant health will also require the use of advanced molecular techniques and imaging (Wu *et al*., 2023; Rajguru *et al*., 2024) [65, 44]. Also, multidisciplinary cooperation among microbiologists, agronomists, data scientists, and policymakers will play a crucial role in establishing integrated and region-specific approaches that will be ecologically sound and can underpin the global food security (Vishwakarma *et al*., 2020; Yusuf *et al*., 2025; Kumawat *et al*., 2021; Xing *et al*., 2025) [63, 70, 34, 68]. Overall, strategic utilization of microbial resources, introduction of precision microbiome control, and further development of biotechnological instruments are the way to the future of sustainable agriculture to develop resilient, productive, and environmentally friendly agroecological systems.

Table 4: Emerging Research Directions and Future Prospects

Research Focus	Future Prospects and Needs	Citations
Microbial Consortia & SynComs	Design crop- and region-specific communities for enhanced resilience and nutrient cycling	(Zuluaga *et al*., 2024; Baloch *et al*., 2024; Yusuf *et al*., 2025; Rajguru *et al*., 2024) [73, 7, 70, 44]
Omics & Systems Biology	Apply metagenomics, metabolomics, and transcriptomics to decode plant-microbe interactions.	(Zuluaga *et al*., 2024; Baloch *et al*., 2024; Rajguru *et al*., 2024) [73, 7, 44]
Microalgae & Cyanobacteria	Scale up inoculum production, optimize deployment, and test across diverse soils.	(Alvarez *et al*., 2021) [3]
Actinobacteria & Endophytes	Advance synthetic biology, nanotech, and field validation for bioinoculant development	(Boubekri *et al*., 2022; Anand *et al*., 2023; Ayilara *et al*., 2022) [11, 4, 6]
Phosphorus-Solubilizing Microbes	Discover new strains, clarify mechanisms, and develop robust field-ready bioformulations	(Silva *et al*., 2023; Chen *et al*., 2024) [51, 15]
Standardization & Field Protocols	Establish protocols for trials, quality control, and farmer education	(Zuluaga *et al*., 2024; Samantaray *et al*., 2024) [73, 47]
Soil Health & Microbial Diversity	Study long-term impacts, necromass dynamics, and climate interactions	(Wu *et al*., 2023; Al-Shammary *et al*., 2024; Chen *et al*., 2024) [65, 2, 15]
Interdisciplinary Collaboration	Integrate microbiology, agronomy, data science, and policy for sustainable solutions.	(Vishwakarma *et al*., 2020; Yusuf *et al*., 2025; Kumawat *et al*., 2021; Xing *et al*., 2025) [63, 70, 34, 68]

Conclusion

Nutrient cycling by means of microbes is an important part of sustaining the soil, ecosystem stability, and agricultural productivity. Microorganisms are natural bio-transformers, and they use their biochemical mechanisms to convert the unavailable forms of key nutrients like nitrogen, phosphorus, and micronutrients to form plant-available forms (through biochemical processes, nitrogen fixation, nitrification, denitrification, phosphate solubilization, and siderophore production). These processes not only increase the availability of nutrients but also increase the soil structure, the microbial diversity, and the health of the soil. By adopting nutrient management practices that incorporate positive microbes, one can achieve a significant role in limiting the use of chemical fertilizers, limiting loss of nutrients, and excessive pollution of the environment. Additionally, application of microbial inoculants and biofertilizers is associated with sustainable production of crops because it increases the efficiency of nutrient use and is also eco-friendly. Nevertheless, the cycling of microbial nutrients depends on the environmental conditions, the type of soil, and the management practices, which must be optimized carefully. The future agricultural systems have to be concerned with exploiting microbial potential by using sophisticated biotechnological methods, including, but not limited to, metagenomics, microbial engineering, and the development of multi-functional microbial consortia. Research, policy reinforcement, and awareness of farmers are to be strengthened to implement microbial innovations on the field level. Altogether, microbial mediation is one of the key aspects of sustainable nutrient cycling that guarantees the long-term soil productivity, environmental safety, and food security on the planet.

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