Soil microbes expertly balancing nutrient demands and environmental preservation and ensuring the delicate stability of our ecosystems- A Review

Abstract

It scrutinizes the critical role of soil microbes in balancing nutrient demands and environmental preservation, thereby ensuring the stability of our ecosystems. The document elucidates how these microscopic organisms play a pivotal role in various ecosystem processes such as nutrient cycling, organic matter decomposition, and the promotion of plant health. It details how their metabolic processes influence soil fertility and plant growth, maintaining a fine equilibrium between the soil's nutrient demand and environmental conservation.The review stresses the influence of microbes on soil health and their potential role in mitigating climate change through carbon sequestration, demonstrating their significance beyond primary production. The correlation between microbial communities, climate change, and soil degradation is emphasized, showing how these factors interact in a complex, interconnected network.Modern microbial management strategies, highlighting sustainable methods to exploit their potential in agriculture and environmental conservation. It advocates for more research into soil microbiome functionality, with a special focus on the impact of human activities and climate change. By emphasizing that soil microbes, although invisible, carry profound implications for global sustainability and food security. By optimizing microbial functions, we can improve soil health and fertility, contributing significantly to ecosystem resilience and stability.

Introduction

Soil microorganisms, commonly known as soil microbes, represent a substantial fraction of the world's biodiversity, existing in complex and diverse communities within the soil environment [1]. These tiny, unseen organisms include a myriad of species, types, and classes that include bacteria, fungi, archaea, viruses, algae, and protozoa, amongst others [2].These organisms are instrumental in the soil ecosystem, existing in intricate networks that interact and collaborate to drive several vital processes in the soil. The collective action of these microorganisms significantly influences the biochemical characteristics of soil, contributing to its productivity and overall health [3].Soil microorganisms play numerous and varied roles within the environment, contributing to essential functions that range from nutrient cycling to climate regulation, disease suppression, decomposition of organic matter, and soil formation [4].One of the primary roles of soil microbes is in the cycling of essential nutrients within ecosystems, transforming inaccessible forms of nutrients into accessible ones that can be utilized by plants and other organisms [5]. This includes key cycles like the nitrogen cycle, where soil microbes convert atmospheric nitrogen into nitrate or ammonium, usable forms for plant growth, or the carbon cycle, where microbes break down organic matter, releasing carbon dioxide back into the atmosphere [6].Soil microbes contribute to the suppression of diseases through competition and inhibition of pathogens, a role that supports plant health and reduces the occurrence of disease outbreaks within ecosystems [7]. Through the process of decomposition, microbes help in the breakdown of dead organic material, contributing to soil fertility and structure, and ultimately to soil formation [8].

Soil microbes in balancing nutrient demands and environmental preservation

The role of soil microbes in balancing nutrient demands and environmental preservation is becoming increasingly understood and appreciated. Microbes mediate the flow of nutrients in soil by breaking down complex organic materials into simpler compounds that plants can absorb and utilize [9]. Through these mechanisms, soil microbes indirectly contribute to plant growth and productivity, thus playing a crucial role in agriculture and food production [10].Soil microbes influence environmental preservation in several ways. By participating in carbon sequestration, they contribute to climate change mitigation. Soil microbes' activity in the decomposition of organic materials and stabilization of organic matter can lead to the sequestration of carbon in the soil, thus reducing the amount of carbon dioxide in the atmosphere [11].By fostering soil health and structure, soil microbes help prevent soil erosion and degradation, maintaining the functionality and productivity of terrestrial ecosystems [12]. These roles of soil microbes are not only vital for the ecosystems they inhabit but are also essential for the well-being and survival of human societies [13].Given their significance, understanding the complex roles of soil microbes and their interactions with the environment is crucial for the development of sustainable land use practices, effective soil management strategies, and potentially mitigating the effects of climate change.This review aims to expand the current understanding of the integral roles of soil microbes in nutrient cycling and environmental preservation, alongside addressing the existing research gaps and upcoming trends in the field.

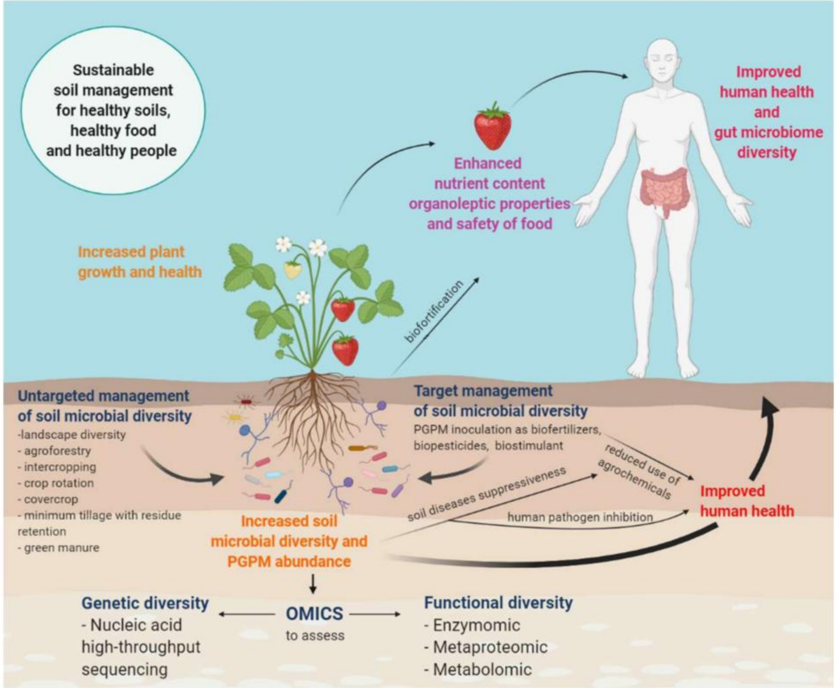

Figure 1: Both targeted and untargeted management of soil microbial diversity in the sustainable improvement of plant health, food crop yield, its nutritional quality and safety.(Source:https://www.mdpi.com/)

Soil microbes' role in nutrient cycling and environmental preservation

Soil microbes form the cornerstone of various biogeochemical processes, including nutrient cycling, which is the movement and exchange of organic and inorganic matter back into the production of living matter (Table 1)[14]. They decompose organic material, releasing essential nutrients into the soil, which plants and other organisms then use for growth [15]. Microorganisms, particularly bacteria and fungi, carry out the mineralization of nutrients, making them available to plants in a form they can assimilate [16]. For instance, nitrogen-fixing bacteria convert atmospheric nitrogen into nitrates, a form that plants can utilize, while other types of bacteria are instrumental in the cycling of phosphorus, sulfur, and other nutrients [17].Soil microorganisms are instrumental in preserving the environment. They contribute to soil health and structure, thereby preventing soil erosion and degradation, while also influencing climate change through their role in carbon sequestration [18]. By decomposing organic matter, soil microbes participate in the carbon cycle, contributing to the sequestration of carbon within the soil [19]. Such activity is crucial for mitigating the increase of atmospheric carbon dioxide levels, a significant driver of global climate change [20].Despite the significant body of knowledge accumulated over recent years, there is still much we don't understand about soil microbes, given their vast diversity and complex interactions in the soil ecosystem [21]. Current understanding remains limited regarding the intricacies of these microbial processes and how they are affected by external factors such as changes in climate, land use, and farming practices.

Table: 1 Role of Soil Microbes in Nutrient Cycling and Environmental Preservation

Soil Microbe	Role in Nutrient Cycling	Role in Environmental Preservation
Nitrogen-fixing Bacteria	Converts atmospheric nitrogen into a form plants can use, enhancing soil fertility.	By reducing dependence on synthetic nitrogen fertilizers, they help prevent water and air pollution.
Mycorrhizal Fungi	Helps plants absorb nutrients, especially phosphorus, from the soil.	Helps in soil structure formation and prevention of soil erosion.
Decomposer Bacteria and Fungi	Breaks down organic matter, recycling nutrients back into the soil.	Contributes to the carbon cycle, supporting soil carbon sequestration and reducing greenhouse gas emissions.
Denitrifying Bacteria	Converts nitrates in the soil back into nitrogen gas.	Prevents excess nitrogen from polluting water bodies.
Sulfur-reducing Bacteria	Converts sulfate to sulfide, aiding in sulfur cycling.	Prevents sulfur buildup, which can lead to soil acidification.

Research gaps and emerging trends in the field

There are several research gaps and emerging trends in the field of soil microbiology that this review aims to address. For one, there is a need for more in-depth studies on the relationship between microbial diversity and ecosystem functions [22]. Although researchers recognize that diversity plays a role in the resilience and stability of soil functions, exactly how this happens is not entirely understood [23].As we move toward a future of increasing climate unpredictability, there is a need to understand how changes in temperature, rainfall, and other climatic factors affect soil microbial communities and their functions [24].The development of high-throughput sequencing technologies and metagenomics has revolutionized the field of soil microbiology, allowing for more comprehensive and accurate studies of soil microbial communities than ever before. As such, it's expected that future research will be able to address some of these gaps and deepen our understanding of soil microbes.There's an emerging trend in employing soil microbiome engineering for sustainable agricultural practices [25]. Researchers are beginning to explore how we might manipulate soil microbial communities to improve soil health and crop productivity, offering a potential tool for sustainable farming and food production in the face of growing environmental challenges.

Soil Microbes and Nutrient Cycling

Nutrient cycling is the process through which nutrients move from the physical environment into living organisms, and then are recycled back into the physical environment [26]. This cycling occurs as organisms extract nutrients from their environment for growth, and then release these nutrients back into the environment through decomposition and waste excretion.Nutrients involved in these cycles include, but are not limited to, carbon, nitrogen, phosphorus, and sulfur, which are essential elements for all life forms [27]. The cycling of these nutrients often involves complex biochemical transformations, many of which are mediated by soil microorganisms.Eg. The nitrogen cycle involves several steps, including nitrogen fixation, nitrification, and denitrification, all mediated by different groups of bacteria [28]. In nitrogen fixation, certain bacteria convert atmospheric nitrogen into ammonium, which can be taken up by plants. Through nitrification, other bacteria transform this ammonium into nitrate, which is also plant-accessible. Finally, in denitrification, yet other bacteria convert nitrates back into atmospheric nitrogen.

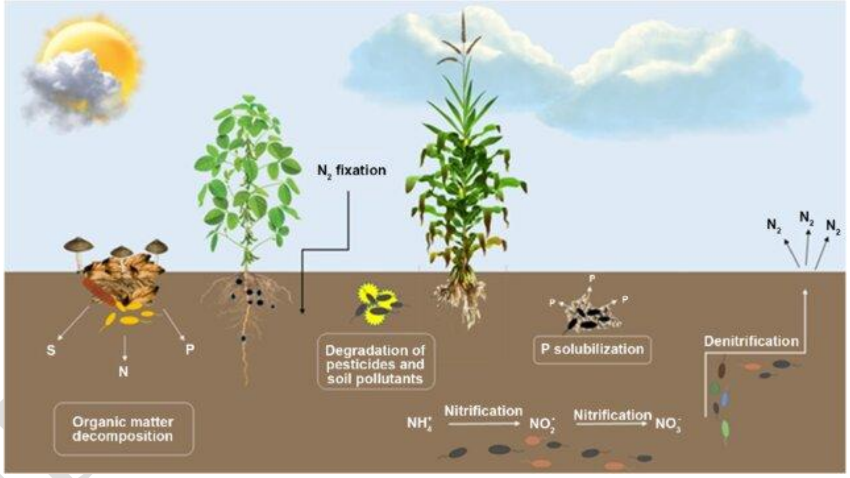

Figure 2: Soil Microbes and Nutrient Cycling(Source: http://www.scirp.org)

Nutrient cycling in ecosystems

Nutrient cycling is of critical importance in all ecosystems, from the smallest pond to the largest forest. It is an essential process for life, ensuring the continued availability of necessary elements for biological processes [29]. These are vital in determining the productivity of ecosystems. The rates at which nutrients cycle influence the amounts of nutrients available for plant growth and consequently the overall primary productivity of an ecosystem [30]. It is integral to soil fertility and health, with implications for agriculture and food production. Healthy soils with active nutrient cycles can support robust plant growth and high crop yields [31].Understanding nutrient cycling processes also has significant implications for environmental sustainability and climate change mitigation. For instance, the carbon cycle is integral to the global carbon budget and thus has direct implications for atmospheric CO_2 levels and climate change [32].

Soil Microbes in Nutrient Cycling

Soil microbes are the primary agents of nutrient transformations in soil, playing a crucial role in the cycling of nutrients through the biosphere [33]. They perform an array of biochemical processes that convert nutrients between various forms, some accessible to plants and other organisms, and others not.A fundamental mechanism through which soil microbes facilitate nutrient cycling is the decomposition of organic matter. During this process, microbes metabolize organic materials, releasing simpler, mineral forms of nutrients in the process [34]. This nutrient release, often called mineralization, provides nutrients in a form that can be taken up by plants.Microbes also participate in the immobilization of nutrients, the opposite of mineralization. This process occurs when microbes take up nutrients from the soil solution, incorporating them into their own biomass [35]. Immobilization temporarily locks nutrients in organic form, making them unavailable to plants.The balance between mineralization and immobilization processes, primarily regulated by soil microbial activity, determines the availability of nutrients in the ecosystem, influencing plant productivity and other ecosystem processes.

Nutrient cycles

Different soil microbes specialize in various parts of nutrient cycles, largely due to their metabolic capacities.

Nitrogen Cycle: Nitrogen is an essential element for all life, yet its most abundant form (N_2 gas) is inaccessible to most organisms. Certain bacteria, known as diazotrophs, can convert N_2 into biologically available forms in a process called nitrogen fixation. Examples include Rhizobium, which forms symbiotic relationships with legumes, and free-living bacteria like Azotobacter [36].Once nitrogen is available in the soil, other bacteria, including Nitrosomonas and Nitrobacter, carry out nitrification, converting ammonium to nitrite and then nitrate, which is more accessible to plants [37].Denitrification, the process of converting nitrate back into atmospheric nitrogen, is performed by various bacteria such as Pseudomonas and Paracoccus under low-oxygen conditions.

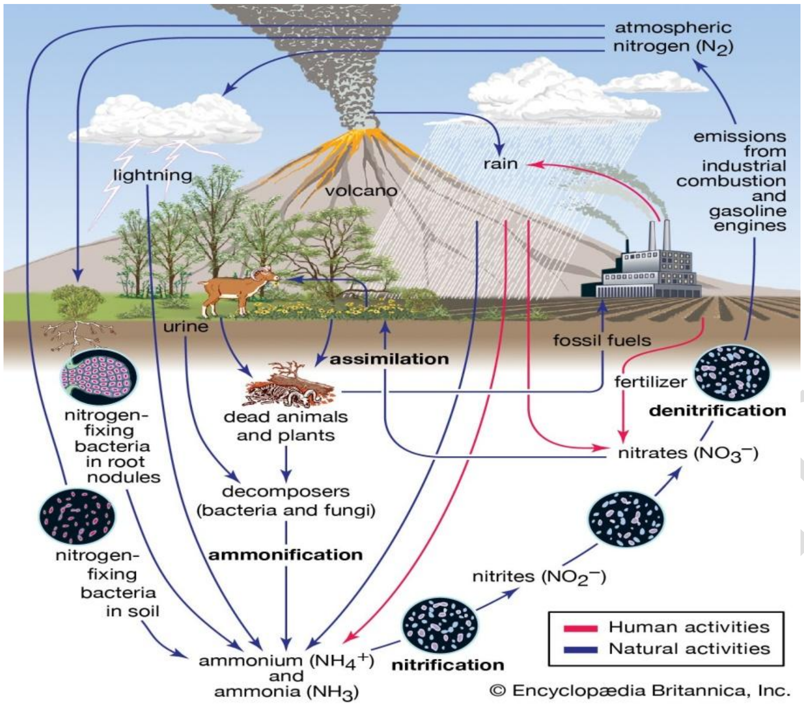

Image 1: Nitrogen Cycle (Source:www.britannica.com)

Phosphorus Cycle: Soil microbes also play a crucial role in the phosphorus cycle. Many soil bacteria and fungi produce enzymes, known as phosphatases, which release inorganic phosphate from organic compounds in the soil, a process referred to as mineralization [38].Certain bacteria, known as phosphate solubilizing bacteria, can make insoluble forms of phosphate accessible to plants.

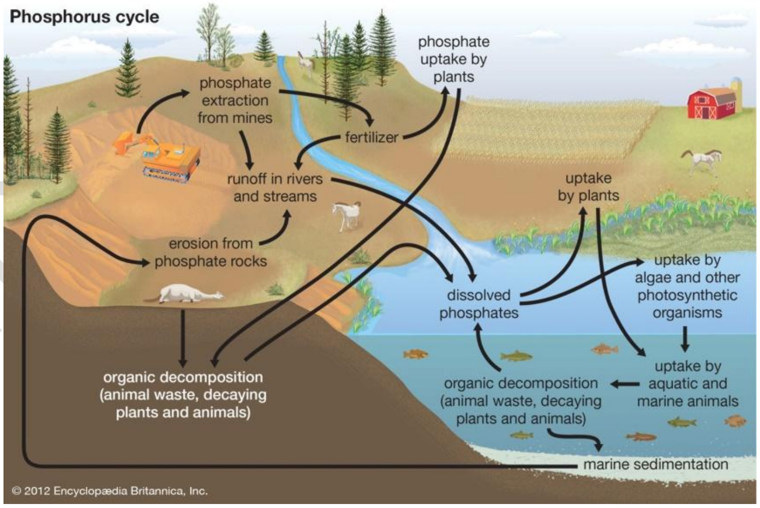

Image 2: Phosphorus Cycle(Source: www.britannica.com)

Sulfur Cycle: Microbes play a role in the sulfur cycle too, transforming sulfur between its organic and inorganic forms. Certain bacteria, such as Desulfovibrio, carry out sulfate reduction under anaerobic conditions, converting sulfate to hydrogen sulfide [39].Other bacteria, like *Thiobacillus*, carry out the opposite process, oxidizing sulfide or other sulfur compounds to sulfate [40].

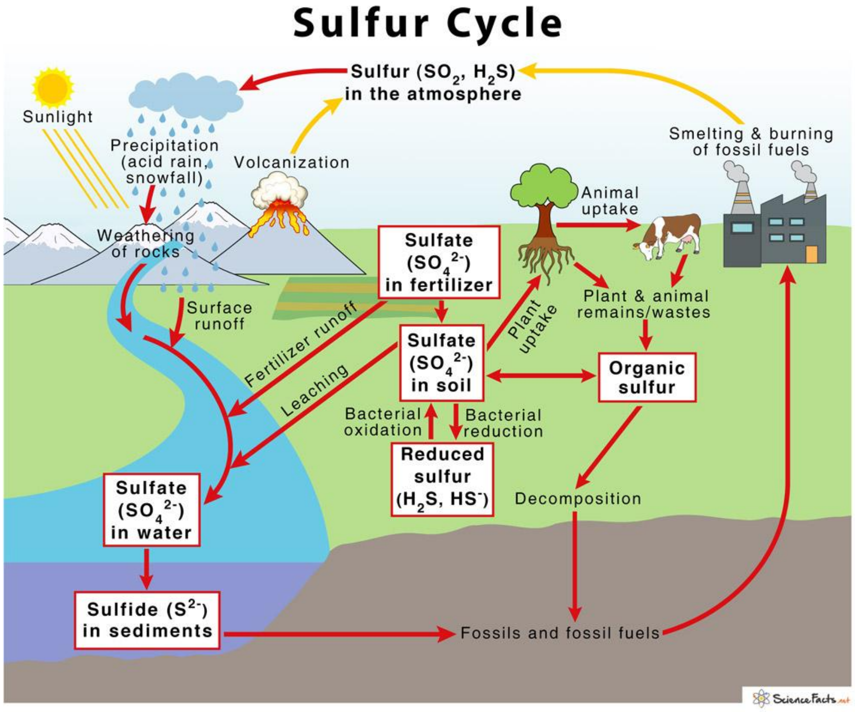

Image 3: Sulphur Cycle (Source: https://www.sciencefacts.net/)

Soil Microbes and Environmental Preservation

Soil fertility, a measure of a soil's ability to support plant growth, is largely governed by its microbial inhabitants. Soil microbes, through their diverse metabolic activities, play a critical role in maintaining and enhancing soil fertility [41].Microbes are vital in nutrient cycling, as they help in the transformation of nutrients from unavailable to available forms for plant uptake, a process often referred to as mineralization [42]. This includes the conversion of nitrogen, phosphorus, and other essential elements into forms that plants can assimilate, enabling the productivity of agroecosystems and natural ecosystems alike [43].Microbes also promote soil fertility through the formation of symbiotic relationships with plants. For instance, mycorrhizal fungi form symbiotic relationships with most plant species, aiding in nutrient uptake, especially phosphorus and nitrogen, which leads to improved plant growth and soil fertility [44]. Soil microbes also contribute to the formation and stabilization of soil aggregates, which enhance soil structure, water holding capacity, and resistance to erosion, all of which are important factors in soil fertility [45].

Soil microbes' role in organic matter decomposition and its importance to soil health

Soil microbes play a crucial role in the decomposition of organic matter, a process vital to soil health. The decomposition of organic materials such as dead plant material, animal waste, and dead microbial cells is primarily performed by a diverse array of soil microbes, including bacteria and fungi [46].The decomposition of organic matter by soil microbes results in the mineralization of nutrients, making them available for plant uptake and thus enhancing soil fertility [47].The by-products of decomposition, including humic substances, contribute to the formation and stabilization of soil aggregates, improving soil structure and water holding capacity [48]. It is also a significant source of soil organic carbon, a critical component of soil health. Soil organic carbon improves soil physical properties, supports the soil microbial community, and enhances the soil's capacity to retain and supply nutrients.Organic matter decomposition by soil microbes also influences soil pH, which in turn affects nutrient availability and microbial activity. Hence, soil microbes, through the decomposition of organic matter, play a pivotal role in maintaining and enhancing soil health.

Soil Microbes and Carbon Sequestration

Carbon sequestration, the long-term capture and storage of carbon dioxide from the atmosphere, is a crucial strategy in combating climate change [49]. It reduces greenhouse gas concentrations in the atmosphere, hence mitigating the global warming potential of carbon dioxide.Soil acts as one of the largest carbon sinks on Earth, harboring approximately 2500 gigatons of carbon, which is more than the amount in the atmosphere and vegetation combined. This ability of soil to capture and store carbon, known as soil carbon sequestration, is a key ecosystem service that contributes significantly to climate change mitigation.Soil carbon sequestration has the potential to offset a significant proportion of the world's annual carbon dioxide emissions, contributing to the objectives of the Paris Agreement to limit global warming to well below 2 ^{o}C above pre-industrial levels [50].To mitigating climate change, soil carbon sequestration improves soil health and productivity, contributing to sustainable agriculture and food security.

Role of soil microbes in carbon sequestration

Soil microbes play a crucial role in soil carbon sequestration. Through the decomposition of organic matter, soil microbes contribute to the formation of humus, a stable form of soil organic carbon that can persist in the soil for decades to centuries [51].Soil bacteria and fungi are primary decomposers in the soil, transforming plant residues and other organic materials into microbial biomass and by-products, some of which are resistant to decomposition and contribute to stable soil carbon pools [52].Mycorrhizal fungi, in particular, play a significant role in carbon sequestration. They form mutualistic symbioses with plants, helping them access nutrients in return for photosynthetically derived carbon.Soil microbes can also influence soil carbon sequestration indirectly by affecting soil physical properties. For example, they contribute to the formation and stabilization of soil aggregates, which can physically protect organic carbon from decomposition, thus enhancing carbon sequestration [53].The role of soil microbes in carbon sequestration, however, is influenced by various factors, including soil type, land use, and climate change. Understanding these influences is crucial for harnessing the potential of soil microbes in carbon sequestration for climate change mitigation.

Challenges and Opportunities

The study and application of soil microbes in environmental science and agriculture face several challenges. One of the fundamental challenges is the complexity and diversity of soil microbial communities. It is estimated that a single gram of soil may contain thousands to millions of microbial species [54]. The sheer number of species and their complex interactions pose a challenge to understanding and manipulating these communities for beneficial purposes.A related challenge is that many soil microbes cannot be cultured in the laboratory using traditional methods, making it difficult to study their functions and interactions [55]. Advances in metagenomics and other culture-independent techniques have enabled the study of these so-called 'unculturable' microbes, but these techniques are often expensive and require specialized knowledge and equipment [56].The effects of global climate change on soil microbial communities and their functions also pose a significant challenge. Changes in temperature, moisture, and other climatic factors can alter microbial community composition and function, affecting nutrient cycling and other ecosystem processes. However, predicting these effects is challenging due to the complexity of microbial responses and their interactions with other components of the ecosystem [57].

Future Opportunities

Despite the challenges, soil microbial research holds immense potential for further research and development. One such area lies in the exploration and harnessing of novel microbial processes. For instance, harnessing microbes capable of fixing atmospheric nitrogen in non-leguminous crops could significantly reduce the reliance on synthetic nitrogen fertilizers, which contribute to environmental pollution [58].There is a need for more research on the implications of climate change on soil microbial communities and their functions, particularly in relation to nutrient cycling and carbon sequestration. Another promising area for research is the role of soil microbes in the phytoremediation of polluted soils. Certain microbes have the ability to degrade or immobilize pollutants, and their use in combination with plants could offer an effective and sustainable solution for soil remediation [59].

Emerging Technologies and Methodologies that Could Enhance Our Understanding and Application of Soil Microbes

Emerging technologies are opening new avenues for the study and application of soil microbes. High-throughput sequencing technologies, for instance, are allowing scientists to explore the immense diversity of soil microbial communities at an unprecedented scale [60].These technologies are being combined with bioinformatics tools to predict the functional potential of microbial communities based on their genetic composition (meta-genomics), offering new insights into their roles in nutrient cycling and other ecosystem processes [61]. Advances in 'omics' technologies (genomics, transcriptomics, proteomics, and metabolomics) are enabling researchers to study soil microbes and their functions at multiple scales, from individual microbes to entire communities [62].New methodologies are being developed for the cultivation and study of 'unculturable' microbes. Techniques such as single-cell genomics and microfluidics allow for the isolation and genomic analysis of individual microbial cells, offering a new perspective on microbial diversity and function [63].Synthetic biology, the design and construction of new biological parts, devices, and systems, also holds promise for the manipulation of soil microbial communities for beneficial purposes, such as enhancing soil fertility or degrading pollutants [64].The field of soil microbial research is on the brink of a new era, driven by technological advances and a growing recognition of the crucial role of soil microbes in sustaining life on Earth.

Conclusion

Soil microbes play a critical role in maintaining the balance of nutrient demands and environmental preservation. Despite facing challenges such as diversity in microbial communities, difficulty in culturing microbes, and the impacts of climate change, the potential for future research and advancements is significant. Emerging technologies and methodologies are continually expanding our understanding of these essential organisms. Harnessing the potential of soil microbes through novel processes, climate change resilience, and remediation strategies represents a promising avenue for enhancing soil health, productivity, and sustainability. Continued exploration and research in this field is crucial for the preservation of our delicate ecosystems.

References

1. Chen, W., Wang, J., Chen, X., Meng, Z., Xu, R., Duoji, D., ... & Zhang, Y. (2022). Soil microbial network complexity predicts ecosystem function along elevation gradients on the Tibetan Plateau. *Soil Biology and Biochemistry*, *172*, 108766.
2. Caron, D. A. (2009). New accomplishments and approaches for assessing protistan diversity and ecology in natural ecosystems. *Bioscience*, *59*(4), 287-299.
3. Bargali, S. S., Padalia, K., &Bargali, K. (2019). Effects of tree fostering on soil health and microbial biomass under different land use systems in the Central Himalayas. *Land Degradation & Development*, *30*(16), 1984-1998.
4. Yadav, A. N., Kour, D., Kaur, T., Devi, R., Yadav, A., Dikilitas, M., ... & Saxena, A. K. (2021). Biodiversity, and biotechnological contribution of beneficial soil microbiomes for nutrient cycling, plant growth improvement and nutrient uptake. *Biocatalysis and Agricultural Biotechnology*, *33*, 102009.
5. Robertson, G. P., &Groffman, P. M. (2007). Nitrogen transformations. In *Soil microbiology, ecology and biochemistry* (pp. 341-364). Academic Press.
6. Khatoon, H., Solanki, P., Narayan, M., Tewari, L., Rai, J., & Hina Khatoon, C. (2017). Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. *International Journal of Chemical Studies*, *5*(6), 1648-1656.
7. Gu, S., Wei, Z., Shao, Z., Friman, V. P., Cao, K., Yang, T., ... &Jousset, A. (2020). Competition for iron drives phytopathogen control by natural rhizosphere microbiomes. *Nature Microbiology*, *5*(8), 1002-1010.
8. Kononova, M. M. (2013). *Soil organic matter: its nature, its role in soil formation and in soil fertility*. Elsevier.
9. Sharma, P. (2022). Role and significance of biofilm-forming microbes in phytoremediation-a review. *Environmental technology & innovation*, *25*, 102182.
10. Kumar, A., Bahadur, I., Maurya, B. R., Raghuwanshi, R., Meena, V. S., Singh, D. K., & Dixit, J. (2015). Does a plant growth-promoting rhizobacteria enhance agricultural sustainability. *J Pure ApplMicrobiol*, *9*(1), 715-724.

11. Bolan, N. S., Kunhikrishnan, A., Choppala, G. K., Thangarajan, R., & Chung, J. W. (2012). Stabilization of carbon in composts and biochars in relation to carbon sequestration and soil fertility. *Science of the Total Environment*, *424*, 264-270.
12. Doran, J. W., Jones, A. J., Arshad, M. A., & Gilley, J. E. (2018). Determinants of soil quality and health. In *Soil quality and soil erosion* (pp. 17-36). CRC Press.
13. Haines-Young, R., &Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. *Ecosystem Ecology: a new synthesis*, *1*, 110-139.
14. Rasmussen, S., Chen, L., Nilsson, M., & Abe, S. (2003). Bridging nonliving and living matter. *Artificial life*, *9*(3), 269-316.
15. Chen, J. H. (2006, October). The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. In *International workshop on sustained management of the soil-rhizosphere system for efficient crop production and fertilizer use* (Vol. 16, No. 20, pp. 1-11). Land Development Department Bangkok Thailand.
16. Hodge, A., Robinson, D., & Fitter, A. (2000). Are microorganisms more effective than plants at competing for nitrogen?. *Trends in plant science*, *5*(7), 304-308.
17. Harindintwali, J. D., Zhou, J., Muhoza, B., Wang, F., Herzberger, A., & Yu, X. (2021). Integrated eco-strategies towards sustainable carbon and nitrogen cycling in agriculture. *Journal of Environmental Management*, *293*, 112856.
18. Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, *15*, 79-86.
19. Zhu, Y. G., & Miller, R. M. (2003). Carbon cycling by arbuscular mycorrhizal fungi in soil–plant systems. *Trends in plant science*, *8*(9), 407-409.
20. Grimmond, S. U. E. (2007). Urbanization and global environmental change: local effects of urban warming. *The Geographical Journal*, *173*(1), 83-88.
21. Turbé, A., De Toni, A., Benito, P., Lavelle, P., Lavelle, P., Camacho, N. R., ... & Mudgal, S. (2010). Soil biodiversity: functions, threats and tools for policy makers.
22. Schimel, J. (1995). Ecosystem consequences of microbial diversity and community structure. *Arctic and alpine biodiversity: patterns, causes and ecosystem consequences*, 239-254.
23. Walker, B., & Salt, D. (2012). *Resilience thinking: sustaining ecosystems and people in a changing world*. Island press.
24. Classen, A. T., Sundqvist, M. K., Henning, J. A., Newman, G. S., Moore, J. A., Cregger, M. A., ... & Patterson, C. M. (2015). Direct and indirect effects of climate change on soil microbial and soil microbial-plant interactions: What lies ahead?. *Ecosphere*, *6*(8), 1-21.
25. Arif, I., Batool, M., & Schenk, P. M. (2020). Plant microbiome engineering: expected benefits for improved crop growth and resilience. *Trends in Biotechnology*, *38*(12), 1385-1396.
26. Vanni, M. J. (2002). Nutrient cycling by animals in freshwater ecosystems. *Annual Review of Ecology and Systematics*, *33*(1), 341-370.

27. Burgin, A. J., Yang, W. H., Hamilton, S. K., & Silver, W. L. (2011). Beyond carbon and nitrogen: how the microbial energy economy couples elemental cycles in diverse ecosystems. *Frontiers in Ecology and the Environment*, *9*(1), 44-52.
28. Pajares, S., & Bohannan, B. J. (2016). Ecology of nitrogen fixing, nitrifying, and denitrifying microorganisms in tropical forest soils. *Frontiers in microbiology*, *7*, 1045.
29. Massoud, T. F., & Gambhir, S. S. (2003). Molecular imaging in living subjects: seeing fundamental biological processes in a new light. *Genes & development*, *17*(5), 545-580.
30. Schuur, E. A., & Matson, P. A. (2001). Net primary productivity and nutrient cycling across a mesic to wet precipitation gradient in Hawaiian montane forest. *Oecologia*, *128*, 431-442.
31. Lehman, R. M., Acosta-Martinez, V., Buyer, J. S., Cambardella, C. A., Collins, H. P., Ducey, T. F., ... & Stott, D. E. (2015). Soil biology for resilient, healthy soil. *Journal of Soil and Water Conservation*, *70*(1), 12A-18A.
32. Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., ... &Melack, J. (2007). Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems*, *10*, 172-185.
33. Zhu, Y., Duan, G., Chen, B., Peng, X., Chen, Z., & Sun, G. (2014). Mineral weathering and element cycling in soil-microorganism-plant system. *Science China: Earth Sci-ences*, *doi*, *10*.
34. Sokol, N. W., Slessarev, E., Marschmann, G. L., Nicolas, A., Blazewicz, S. J., Brodie, E. L., ... &Pett-Ridge, J. (2022). Life and death in the soil microbiome: how ecological processes influence biogeochemistry. *Nature Reviews Microbiology*, *20*(7), 415-430.
35. Zumstein, M. T., Schintlmeister, A., Nelson, T. F., Baumgartner, R., Woebken, D., Wagner, M., ... & Sander, M. (2018). Biodegradation of synthetic polymers in soils: Tracking carbon into CO2 and microbial biomass. *Science advances*, *4*(7), eaas9024.
36. Philippot, L., &Germon, J. C. (2005). Contribution of bacteria to initial input and cycling of nitrogen in soils. *Microorganisms in soils: roles in genesis and functions*, 159-176.
37. Tamme, T., Reinik, M., &Roasto, M. (2010). Nitrates and nitrites in vegetables: occurrence and health risks. In *Bioactive Foods in Promoting Health* (pp. 307-321). Academic Press.
38. Tian, J., Ge, F., Zhang, D., Deng, S., & Liu, X. (2021). Roles of phosphate solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical P cycle. *Biology*, *10*(2), 158.
39. Long, Y., Fang, Y., Shen, D., Feng, H., & Chen, T. (2016). Hydrogen sulfide (H2S) emission control by aerobic sulfate reduction in landfill. *Scientific reports*, *6*(1), 38103.
40. Tang, K., Baskaran, V., & Nemati, M. (2009). Bacteria of the sulphur cycle: an overview of microbiology, biokinetics and their role in petroleum and mining industries. *Biochemical Engineering Journal*, *44*(1), 73-94.

41. Abinandan, S., Subashchandrabose, S. R., Venkateswarlu, K., &Megharaj, M. (2019). Soil microalgae and cyanobacteria: the biotechnological potential in the maintenance of soil fertility and health. *Critical reviews in biotechnology*, *39*(8), 981-998.
42. Moreau, D., Bardgett, R. D., Finlay, R. D., Jones, D. L., &Philippot, L. (2019). A plant perspective on nitrogen cycling in the rhizosphere. *Functional Ecology*, *33*(4), 540-552.
43. Nicholls, C. I., Altieri, M. A., & Vazquez, L. (2017). Agroecological principles for the conversion of farming systems. In *Agroecological Practices For Sustainable Agriculture: Principles, Applications, And Making The Transition* (pp. 1-18).
44. Pal, A., & Pandey, S. (2014). Role of glomalin in improving soil fertility. *International journal of plant and soil science*, *3*, 112-29.
45. Bot, A., &Benites, J. (2005). The importance of soil organic matter: Key to drought-resistant soil and sustained food production (No. 80). *Food & Agriculture Org.*.
46. Khatoon, H., Solanki, P., Narayan, M., Tewari, L., Rai, J., & Hina Khatoon, C. (2017). Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. *International Journal of Chemical Studies*, *5*(6), 1648-1656.
47. Fontaine, S., Mariotti, A., &Abbadie, L. (2003). The priming effect of organic matter: a question of microbial competition?. *Soil Biology and Biochemistry*, *35*(6), 837-843.
48. Boyle, M., Frankenberger Jr, W. T., &Stolzy, L. H. (1989). The influence of organic matter on soil aggregation and water infiltration. *Journal of production agriculture*, *2*(4), 290-299.
49. Klass, A. B., & Wilson, E. J. (2008). Climate change and carbon sequestration: Assessing a liability regime for long-term storage of carbon dioxide. *Emory LJ*, *58*, 103.
50. Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., ... &Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature*, *534*(7609), 631-639.
51. Schaeffer, A., Nannipieri, P., Kästner, M., Schmidt, B., &Botterweck, J. (2015). From humic substances to soil organic matter–microbial contributions. In honour of Konrad Haider and James P. Martin for their outstanding research contribution to soil science. *Journal of Soils and Sediments*, *15*, 1865-1881.
52. Horwath, W. (2007). Carbon cycling and formation of soil organic matter. In *Soil microbiology, ecology and biochemistry* (pp. 303-339). Academic Press.
53. Six, J., Frey, S. D., Thiet, R. K., & Batten, K. M. (2006). Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Science Society of America Journal*, *70*(2), 555-569.
54. Dykhuizen, D. E. (1998). Santa Rosalia revisited: why are there so many species of bacteria?. *Antonie van Leeuwenhoek*, *73*, 25-33.
55. Dror, B., Jurkevitch, E., &Cytryn, E. (2020). State-of-the-art methodologies to identify antimicrobial secondary metabolites in soil bacterial communities-A review. *Soil Biology and Biochemistry*, *147*, 107838.

56. Fraher, M. H., O'toole, P. W., & Quigley, E. M. (2012). Techniques used to characterize the gut microbiota: a guide for the clinician. *Nature reviews Gastroenterology & hepatology*, *9*(6), 312-322.
57. Pendall, E., Bridgham, S., Hanson, P. J., Hungate, B., Kicklighter, D. W., Johnson, D. W., ... & Wan, S. (2004). Below-ground process responses to elevated CO_2 and temperature: a discussion of observations, measurement methods, and models. *New Phytologist*, *162*(2), 311-322.
58. Sheoran, S., Kumar, S., Kumar, P., Meena, R. S., &Rakshit, S. (2021). Nitrogen fixation in maize: breeding opportunities. *Theoretical and Applied Genetics*, *134*, 1263-1280.
59. Vishnoi, S. R., & Srivastava, P. N. (2007, October). Phytoremediation–green for environmental clean. In *Proceedings of Taal2007: the 12th World lake conference* (Vol. 1016, p. 1021).
60. HUSSEIN, I. I. (2020). Metagenomics: Unravelling the uncultured microbial community. *BIMA JOURNAL OF SCIENCE AND TECHNOLOGY (2536-6041)*, *3*(02), 48-58.
61. Heidelberg, K. B., Gilbert, J. A., & Joint, I. (2010). Marine genomics: at the interface of marine microbial ecology and biodiscovery. *Microbial biotechnology*, *3*(5), 531-543.
62. Desai, C., Pathak, H., &Madamwar, D. (2010). Advances in molecular and "-omics" technologies to gauge microbial communities and bioremediation at xenobiotic/anthropogen contaminated sites. *Bioresource Technology*, *101*(6), 1558-1569.
63. Marcy, Y., Ouverney, C., Bik, E. M., Lösekann, T., Ivanova, N., Martin, H. G., ... & Quake, S. R. (2007). Dissecting biological "dark matter" with single-cell genetic analysis of rare and uncultivated TM7 microbes from the human mouth. *Proceedings of the National Academy of Sciences*, *104*(29), 11889-11894.
64. Lawson, C. E., Harcombe, W. R., Hatzenpichler, R., Lindemann, S. R., Löffler, F. E., O'Malley, M. A., ... & McMahon, K. D. (2019). Common principles and best practices for engineering microbiomes. *Nature Reviews Microbiology*, *17*(12), 725-741.