A review of long-term effects of mineral fertilizers on soil microorganisms

Abstract

The intricate relationship between soil microbiomes and fertilizers is central to the sustainable future of agriculture. This review delves deep into the multifaceted interactions between soil microorganisms and varying fertilizer regimens, shedding light on their immediate and long-term impacts. Soil, teeming with a rich diversity of bacteria, fungi, archaea, protozoa, and viruses, plays a pivotal role in agricultural productivity. These microbial communities are intricately linked to soil health, fertility, and resilience. Fertilizers, while essential for enhancing crop yields, have shown varied impacts on these microbial communities. Immediate post-application dynamics reveal shifts in microbial diversity and abundance, with potential cascading effects on soil processes. Longitudinal studies in real-world agricultural settings underscore the resilience and adaptability of these communities in the face of disturbances. Advanced technological tools, from metagenomics to IoT devices, offer unprecedented insights and real-time monitoring capabilities. The convergence of biology with technology holds the promise of a future where agricultural practices are fine-tuned based on real-time microbial feedback, ensuring both enhanced yields and sustained soil health. As we stand at the crossroads of a global food demand surge and environmental sustainability, understanding and harnessing the potential of soil microbiomes becomes paramount. This review underscores the need for robust, long-term research endeavors to chart a path for truly sustainable agriculture.

Keywords: *Microbiomes, Fertilizers, Sustainability, Agriculture, Metagenomics*

Introduction

Soil, often termed as the skin of the Earth, is more than just the medium that anchors plants by their roots. It is a complex and vibrant ecosystem teeming with diverse life forms, the smallest yet among the most significant of which are soil microorganisms. These microscopic entities are the unsung heroes of the soil matrix, playing pivotal roles in ensuring soil health and, by extension, global food security. This review aims to shed light on the critical importance of these microorganisms and to understand the role and implications of mineral fertilizers in modern agriculture.Soil microorganisms include a vast range of bacteria, fungi, protozoa, and algae. Though minuscule in size, their impact on the soil environment and ecosystem at large is colossal. They are the primary agents of nutrient cycling, decomposing organic matter, fixing atmospheric nitrogen, improving soil structure, and enhancing plant health through symbiotic relationships [1].One of the principal contributions of soil microbes is their role in the nutrient cycle. Through the decomposition of organic materials, microorganisms release essential nutrients into the soil, making them available for plant uptake. This process is the backbone of soil fertility. Certain bacteria, known as diazotrophs, can fix atmospheric nitrogen, converting it into forms accessible to plants. Given that nitrogen is one of the primary limiting nutrients for plant growth, this activity profoundly influences plant productivity and, thus, ecosystem dynamics.Beyond nutrient cycling, soil microorganisms influence the physical properties of soil. Through their metabolic activities and the substances they excrete, microbes can improve soil structure, promoting aggregation, which increases the soil's capacity to retain water and resist erosion [2]. Soil microbes play a protective role. They compete with potential pathogenic microorganisms, preventing diseases. In some cases, they form symbiotic relationships with plants, providing them with nutrients while receiving organic compounds in return. Mycorrhizal fungi, for instance, enhance plant access to phosphorus and other nutrients in exchange for photosynthetic sugars from the plant [3].

Mineral Fertilizers in Modern Agriculture

With the global population soaring, there has been an unprecedented demand for food. Modern agriculture, in its bid to meet this demand, has turned to various technological and scientific innovations. One of the most transformative of these innovations has been the use of mineral fertilizers.Mineral fertilizers are synthesized compounds or mined substances that supply essential nutrients to plants. The three primary nutrients commonly found in these fertilizers are nitrogen (N), phosphorus (P), and potassium (K). They are often referred to by the N-P-K value indicating their composition (Table 1). While traditional farming relied heavily on organic manure and compost, the advent of mineral fertilizers brought about a revolution, enabling increased food production at scales previously unimagined [4].The Green Revolution in the mid-20th century stands as a testament to the power of mineral fertilizers. Countries that were once grappling with food shortages transformed into grain-surplus nations. Fertilizers, along with improved crop varieties and irrigation, brought about significant yield improvements. Crops that were once nutrient-starved now had a consistent and concentrated source of essential nutrients, leading to better growth and increased productivity. As with all great innovations, there are associated challenges. Over-reliance on mineral fertilizers, without considering the natural biological processes of the soil, can lead to a range of environmental issues, including eutrophication of water bodies, greenhouse gas emissions, and even degradation of the soil's physical structure [5].

Table 1: Overview of Common Mineral Fertilizers Used in Modern Agriculture.

Type of Fertilizer	Primary Nutrients	Typical Application Rates (kg/ha)	Best Suited Crops
Urea	Nitrogen (N)	50-200	Cereals, vegetables
Diammonium Phosphate (DAP)	Nitrogen (N), Phosphorus (P)	80-120	Corn, wheat, soybeans
Monoammonium Phosphate (MAP)	Nitrogen (N), Phosphorus (P)	50-100	Fruits, vegetables
Potassium Chloride (Muriate of Potash)	Potassium (K)	50-100	Root crops, fruit trees
Calcium Ammonium Nitrate	Nitrogen (N), Calcium (Ca)	60-120	Leafy vegetables
Ammonium Sulphate	Nitrogen (N), Sulphur (S)	50-150	Tea, coffee
Superphosphate	Phosphorus (P)	40-80	Flowers, fruits
Magnesium Sulphate	Magnesium (Mg), Sulphur (S)	20-50	Citrus fruits
Triple Superphosphate	Phosphorus (P)	30-60	Legumes
NPK (Compound Fertilizers)	Nitrogen (N), Phosphorus (P), Potassium (K)	100-200	General use

Comment [ME1]: It might be better if you add references in the table.

Long-term Impact of Mineral Fertilizers

Comment [ME2]: Addition of some more findings are recommended.

While the immediate benefits of mineral fertilizers on crop yield are apparent, their long-term implications, especially on soil microorganisms, are complex and multifaceted. Soil, being a dynamic system, responds to external inputs in ways that are not always predictable in the long run.Over-application of mineral fertilizers can lead to nutrient imbalances in the soil. Excessive nitrogen, for instance, can make soils acidic over time, affecting microbial communities that thrive in neutral pH [7]. Such alterations can disrupt the natural processes of nutrient cycling, potentially reducing soil fertility in the long term. The frequent application of fertilizers can lead to a scenario where plants become overly reliant on external nutrient sources, diminishing their symbiotic relationships with certain beneficial microbes. This can make plants more susceptible to diseases and pests, reducing the overall resilience of the ecosystem.Thus, it is of paramount importance to understand the long-term impact of mineral fertilizers, not just from an agricultural productivity standpoint but also for ensuring sustainable and ecologically sound agricultural practices.

Basics of Soil Microbiology

Soil is often referred to as the final frontier in terrestrial biology because it harbors a rich diversity of life, much of which remains uncharacterized. The soil matrix is teeming with a vast array of microorganisms that play crucial roles in the maintenance of soil health, fertility, and ecosystem functioning.Bacteria are unicellular, prokaryotic microorganisms and are among the most prolific entities in the soil. They exist in various shapes ranging from spheres (cocci) to rods (bacilli) and spirals (spirochetes). Bacteria in the soil are involved in several crucial processes, including decomposition, nitrogen fixation, and disease suppression (Table 2). Examples include Azotobacter, which is a free-living nitrogen-fixing bacterium, and Rhizobium, which forms nodules on the roots of leguminous plants and fixes atmospheric nitrogen [8]. Fungi are eukaryotic organisms that play a multifaceted role in the soil. They range from single-celled yeasts to complex multicellular molds and mushrooms. Fungi are primary decomposers in the soil, breaking down complex organic matter and recycling nutrients. Mycorrhizal fungi form mutualistic associations with plant roots, aiding in nutrient uptake, particularly phosphorus [9]. Actinomycetes Often confused with fungi due to their filamentous growth, actinomycetes are actually bacteria. They are known for their ability to decompose complex organic compounds, including cellulose and chitin. Many actinomycetes, like Streptomyces, are known to produce antibiotics, playing a role in suppressing soil-borne diseases [10].Protozoa are single-celled eukaryotic microorganisms are pivotal in controlling bacterial populations in the soil, maintaining a microbial balance. They feed on bacteria and release nutrients in a form that can be utilized by plants and other microorganisms.

Table 2: Key Aspects of Soil Microbiology and Their Importance in Agriculture

Comment [ME3]: It could be better to add references in the table.

Type of Microorganism	Primary Functions	Importance in Agriculture
Bacteria	Nutrient cycling, nitrogen fixation	Enhances soil fertility, plant growth
Fungi	Decomposition, mycorrhizal associations	Increases nutrient uptake, soil structure
Actinomycetes	Decomposition, antibiotic production	Breaks down tough organic matter

Protozoa	Grazing on bacteria, nutrient release	Stimulates microbial activity, nutrient cycling
Algae	Photosynthesis, nitrogen fixation	Adds organic matter, oxygen production
Viruses	Infects other microorganisms	Can control harmful microbe populations
Nematodes	Predation, nutrient cycling	Can be both beneficial and harmful

Microbes in Soil Health and Nutrient Cycling

The aforementioned microbial groups, though minute, shape the health and vitality of the soil. Their activities directly and indirectly influence the physical, chemical, and biological properties of the soil.Decomposition and Organic Matter Breakdown: Bacteria and fungi play a significant role in decomposing dead organic matter. They break down complex compounds like cellulose, lignin, and proteins into simpler compounds. This decomposition process recycles essential nutrients back into the soil, making them available for plant uptake. Actinomycetes, with their ability to decompose cellulose, play a pivotal role in recycling plant material [11].Nitrogen Cycling: Nitrogen is a fundamental component of amino acids, proteins, and DNA, making it essential for all living organisms. Although the Earth's atmosphere is approximately 78% nitrogen, most plants cannot use it in its gaseous form. Bacteria like Rhizobium and Azotobacter fix atmospheric nitrogen, converting it into a form that plants can use. Other bacteria are involved in nitrification and denitrification processes, ensuring the continuous cycling of nitrogen in its various forms in the soil.

Disease Suppression: Certain soil microorganisms have antagonistic effects on soil-borne pathogens. By producing antibiotics, competing for resources, or directly feeding on pathogens, these beneficial microorganisms help in suppressing diseases and maintaining plant health [12].

Soil Structure: Microorganisms, through their metabolic activities and the substances they excrete, influence the soil's physical structure. For instance, fungi produce a sticky protein called glomalin, which aids in soil aggregation. Properly aggregated soil enhances water infiltration, root penetration, and resistance to erosion [13].

Comment [ME4]: Addition of some more discussion will be valuable.

Plants and Soil Microbes

The relationship between plants and soil microbes is multifaceted and largely symbiotic.The rhizosphere, the region surrounding plant roots, is a hotspot of microbial activity. Plants exude sugars, amino acids, and organic acids from their roots, which attract and nourish a diverse community of microorganisms. These microbes, in return, aid the plant in various ways. For instance, mycorrhizal fungi associate with plant roots, increasing their nutrient uptake capacity [14].Some microbes have direct applications in agriculture as biofertilizers. Bacteria like Rhizobium and Azotobacter enhance plant growth by supplying fixed nitrogen. Others, like Pseudomonas and Bacillus, can solubilize phosphorus from the soil, making it available to plants.Some soil microorganisms protect plants from pathogens. They might produce compounds that inhibit pathogens or outcompete them for resources. Actinomycetes, for instance, produce a range of antibiotics that can suppress harmful fungi and bacteria.

Mineral Fertilizers

Mineral fertilizers, categorized into nitrogenous, phosphatic, potassic, and complex types, are central to modern agriculture. Nitrogenous fertilizers like urea are essential for plant growth and contain high nitrogen content [15]. Phosphatic fertilizers, including DAP and SSP, supply phosphorus crucial for energy transfer and DNA formation in plants. Potassic fertilizers like MOP provide potassium for water balance and enzyme activation. Complex fertilizers, such as DAP, offer multiple nutrients.These fertilizers release nutrients in specific forms plants can absorb; for instance, urea converts to ammonium ions in the soil, which can be directly taken up by plants or transformed into nitrates [16]. Application methods include broadcasting, placing, foliar application, and drip irrigation, each with its advantages and limitations. Rates of application depend on soil tests, crop needs, and environmental considerations.

Short-term vs. Long-term Effects

The Green Revolution popularized the use of mineral fertilizers, boosting agricultural yields but also altering soil microbial communities. In the short term, nutrients from fertilizers spur microbial activity, benefiting bacteria that can quickly utilize these added nutrients [17]. However, this can lead to rapid depletion of soil's organic carbon stocks.Over time, these changes can reduce microbial diversity [18] and impact beneficial microbial functions like nitrogen fixation [19]. This has long-term implications for soil health and raises sustainability concerns, including greenhouse gas emissions. Balancing immediate benefits of fertilizers with their long-term impacts necessitates optimized application rates and new technologies for sustainable agriculture.

Long-term Effects on Soil Bacterial Communities

Long-term use of mineral fertilizers significantly alters soil bacterial communities, impacting both their abundance and diversity (Table 3). While fertilizer application initially increases bacterial abundance due to added nutrients [20], it often decreases species diversity. Reduced diversity can affect soil resilience to disturbances like disease outbreaks or climate extremes [21].Shifts also occur in bacterial functional groups. Nitrogenous fertilizers promote bacteria that utilize inorganic nitrogen but reduce the number of nitrogen-fixing bacteria, which naturally replenish soil nitrogen [22]. This impacts other crucial soil processes, such as phosphorus solubilization and organic matter decomposition. Long-term fertilizer use can stimulate denitrifying bacteria, increasing emissions of potent greenhouse gases like nitrous oxide. This compromises both climate stability and soil fertility [23]. The alterations in bacterial communities underline the need to consider the trade-offs between immediate agricultural gains and long-term soil health.

Table 3: Long-term Effects of Different Types of Fertilizers on Soil Bacterial Communities

Type of Fertilizer	Effect on Bacterial Diversity	Effect on Bacterial Abundance	Impact on Specific Bacterial Groups	Long-term Agricultural Implications
Organic Fertilizers	Increases diversity	Increases abundance	Promotes beneficial bacteria like Rhizobium	Improved soil health, nutrient cycling

Comment [ME5]: Please add references in the table (use more column).

Chemical Fertilizers	Decreases diversity	May increase abundance	Can reduce beneficial bacteria, promote opportunistic pathogens	Risk of soil degradation, nutrient imbalance
No Fertilizers	Moderate diversity	Lower abundance	Balanced but less active bacterial communities	Limited nutrient availability, slower plant growth
NPK (Compound Fertilizers)	Varies depending on composition	Varies	Can favor Nitrogen-fixing, Phosphorus-solubilizing bacteria	Enhanced nutrient availability, but risk of imbalance
Slow-release Fertilizers	Moderate to high diversity	Moderate abundance	Balanced bacterial communities	Sustained nutrient release, improved soil structure

Long-term Effects on Soil Fungal Communities

Soil fungal communities, as vital as their bacterial counterparts, experience significant shifts due to long-term mineral fertilizer applications. Mycorrhizal fungi, which have evolved symbiotic relationships with most terrestrial plants, find their roles diminished when phosphorus is abundantly supplied via fertilizers. This altered dynamic compromises not just nutrient uptake, but also the soil's resilience against pathogens and environmental stresses [24].Saprophytic fungi, the decomposers, are influenced by nutrient-rich conditions. While an initial increase in decomposition might seem beneficial, it can lead to long-term depletion of soil organic carbon, impacting soil health. The specialization among saprophytic fungi could also be disrupted, altering soil nutrient cycling [25].Pathogenic fungi, responsible for plant diseases, also experience altered dynamics. High nutrient conditions may favor some pathogenic species, and the reduced presence of beneficial mycorrhizal fungi can make plants more susceptible to these diseases [26].These changes in fungal communities have far-reaching implications for soil health, plant growth, and broader ecosystem functions. As sustainability becomes a focal point in agriculture, understanding these fungal shifts is crucial. Choices in fertilizer type and application rates today will impact the soil's biological fabric for years to come.

Effects on Other Soil Microbes

The impact of long-term mineral fertilizer use extends to a wide range of soil microorganisms including actinomycetes, archaea, and protozoa. Actinomycetes are pivotal for decomposing complex organic substances like lignin and chitin, and they produce antibiotics that suppress soil diseases. However, excessive nitrogen from fertilizers can suppress actinomycetes, affecting soil decomposition and disease resistance [27].Archaea, specifically methanogenic types, play a key role in methane production, an important greenhouse gas. Nitrate-rich fertilizers can inhibit this methane production, affecting global climate dynamics [28].Protozoa serve as microbial predators, influencing both nutrient cycling and microbial community structure. An abundance of nutrients from fertilizers can disrupt this balance, potentially leading to new equilibrium states that could affect nutrient cycling and microbial communities. High nutrient conditions may also trigger protozoa to form cysts, affecting their predatory roles [29].

Physicochemical Changes due to Mineral Fertilizers and their Microbial Impacts

The intricate balance of life in soil hinges not just on the biological components but also on the physicochemical parameters that mold its environment. From the farmer's plough to the scientist's microscope, the soil's physical and chemical properties have always been of paramount significance. Mineral fertilizers, long heralded for their role in enhancing agricultural yields, leave indelible footprints on these properties. And as these physicochemical characteristics change, so do the microbial communities that call the soil their home.One of the most immediate and perceptible impacts of mineral fertilizer application is on soil pH. pH, a measure of soil's acidity or alkalinity, is a master variable in soil science, influencing a plethora of soil functions. Many mineral fertilizers, based on their constituents, can either acidify the soil or make it more alkaline. Ammonium-based fertilizers, for instance, tend to release hydrogen ions as the ammonium is converted to nitrate, leading to a decrease in pH or increased soil acidity. Conversely, lime, often used to rectify acidic soils, increases soil pH. These shifts in pH don't just remain mere numbers on paper. They sculpt the microbial landscape belowground. Each microbial group, be it bacteria, fungi, or actinomycetes, has a preferred pH range. As pH shifts away from this optimum, certain microbial populations can decline while others flourish. Acidic soils, for instance, might favor certain acid-loving fungi while suppressing some bacterial groups. Over the long term, these pH-induced shifts can alter microbial community structures, influencing processes like nutrient cycling, organic matter decomposition, and disease suppression [30].Yet, pH is just one part of the story. Soil organic matter (SOM), a complex mixture of decomposing plant and microbial residues, humic substances, and other organic compounds, is the lifeblood of fertile soils. It enhances soil's water-holding capacity, binds to and releases essential nutrients, and plays a crucial role in soil aggregation. However, the long-term application of mineral fertilizers, by providing plants with readily available nutrients, can sometimes reduce the input of organic residues to the soil. Over years, this can lead to a decline in SOM content. Reduced organic matter can stifle the growth and activity of those microbes, particularly fungi and actinomycetes, which rely on organic substrates for energy and growth. SOM plays a role in buffering soil against pH changes. A decline in SOM can, therefore, exacerbate pH fluctuations induced by mineral fertilizers. As organic matter levels drop, the soil's ability to retain water and nutrients might also diminish, creating an environment less conducive to microbial growth and activity [31].

Indirect Effects of Fertilizer Application

The direct benefits of mineral fertilizers, such as improved crop yields, often overshadow their subtle indirect effects on soil ecosystems [32]. These fertilizers alter root exudates complex compounds secreted by plant roots that facilitate communication with soil microbes. The shift in exudate composition can impact the microbial communities in the rhizosphere, the soil region directly influenced by root activities [33].Additionally, mineral fertilizers can introduce trace elements like heavy metals into the soil, which accumulate over time [34]. This accumulation has repercussions for soil microbes, crucial for soil health, as they become vulnerable to heavy metal toxicity. Such toxicity can inhibit microbial enzymatic activities and reduce microbial diversity (35).The application of mineral fertilizers can also disrupt long-standing symbiotic relationships between plants and microbes. For instance, nitrogen-rich fertilizers may reduce a legume plant's reliance on nitrogen-fixing bacteria [36]. This shift can alter the fabric of plant-microbe symbiosis in agricultural soils, affecting both soil health and crop resilience over time [37]. While the immediate benefits of mineral fertilizers are significant, it's crucial to consider their indirect effects for sustainable agriculture. These hidden impacts on soil ecosystems can have long-term implications for both crop yield and environmental health.

Implications for Soil Health and Productivity

Mineral fertilizers' influence on soil microbial communities is a subject of ongoing research, aiming to unravel the balance between enhanced productivity and long-term soil health. Several studies have identified initial benefits of mineral fertilizers, such as enhanced microbial activity attributed to the immediate availability of essential nutrients [38]. However, there is growing evidence that unregulated and excessive use of these fertilizers can have detrimental impacts on microbial diversity [39].One key area of concern is the disruption of nutrient cycling within the soil microbiome. Soil microbes are instrumental in the decomposition of organic matter and the subsequent release of essential nutrients for plant uptake [40]. Excessive application of nitrogenous fertilizers, in particular, has been shown to disrupt these microbial processes [41]. Such disruptions can result in nutrient imbalances, causing either nutrient deficiencies or toxicities that ultimately affect crop yields [42].The issue is further exacerbated by the advent of climate change. Shifts in weather patterns can introduce additional stress factors that may affect both soil and microbial health. A robust microbial community provides functional redundancy, offering a buffer against such unpredictable stressors [43]. Therefore, the reduction in microbial diversity due to indiscriminate fertilizer application could leave soils and, by extension, agricultural systems more vulnerable to the impacts of climate change [44].

Sustainable Fertilizer Practices

Precision agriculture stands out as a model that leverages technology for more responsible farming. Its data-driven tactics optimize the use of mineral fertilizers, offering a good balance between soil health and agricultural yield. This minimizes the risk of upsetting the delicate microbial balance of the soil, making it a forward-thinking approach that aligns well with sustainability goals.Integrated Nutrient Management (INM) is another cornerstone in the realm of sustainable agricultural practices. Your mention of the symbiotic relationship between organic amendments and soil microbes underscores the importance of a well-rounded nutrient strategy. INM does more than just meet the immediate nutritional needs of crops; it also serves as an investment in the long-term fertility and resilience of the soil.The focus on monitoring soil health, particularly through advanced techniques like metagenomics, adds another layer of complexity and responsibility to farming practices. The genomic profile of soil can serve as an early diagnostic tool, providing a snapshot of the microbial diversity and, by extension, the soil’s overall health. This could revolutionize the way we understand and interact with the very ground that sustains us, making it an integral part of future sustainable practices.Certainly, as we advance in our understanding of soil microbiology and its integral role in agriculture, the necessity for practices like precision agriculture and INM becomes increasingly clear. These aren't just optional approaches but critical components of a sustainable agricultural system that respects both yield and ecological balance. The microbial world beneath our feet is not just a passive recipient of farming practices but an active participant that can offer crucial feedback for sustainable agriculture. Therefore, the future of agriculture may well be a finely tuned dance between technological advancements and microbial ecosystems, each informing and enriching the other.

Future Research Directions

As we deepen our understanding of soil ecosystems and their integral relationship with agriculture, one truth becomes increasingly evident: our knowledge, while substantial, remains only at the precipice of the vast expanse of intricacies this realm offers. The study of soil microbiomes in relation to fertilizer practices, in particular, is a field replete with opportunities and challenges, beckoning researchers to chart new territories and decipher the myriad interactions that sustain life on this planet.Soil, often referred to as the Earth's living skin, is a dynamic matrix where innumerable biotic and abiotic factors interplay. While we have gleaned insights into some of these interactions, particularly concerning macro-organisms and plants, the microscopic world remains shrouded in mystery. Soil microbiomes, consisting of a mind-boggling diversity of bacteria, fungi, archaea, protozoa, and viruses, orchestrate processes fundamental to soil health and, by extension, agricultural productivity. The precise roles, interactions, and adaptive strategies of these microbes, especially in the context of varying fertilizer regimens, are areas that beckon deeper exploration.

Conclusion

In the ever-evolving landscape of soil research, understanding the interplay between fertilizers and soil microbiomes is paramount. As our knowledge expands, it becomes clear that these microscopic entities profoundly influence soil health and agricultural productivity. The intricate balance between soil microorganisms and fertilizers is delicate, with both immediate and long-term implications. Technological advancements provide a promising avenue to delve deeper into these interactions, promising a future where agricultural practices are both informed and sustainable. Investing in focused research in this realm is not merely an academic pursuit but a pressing necessity to ensure a harmonious coexistence of productive agriculture with thriving soil ecosystems.

References

1. Prasad, S., Malav, L. C., Choudhary, J., Kannojiya, S., Kundu, M., Kumar, S., & Yadav, A. N. (2021). Soil microbiomes for healthy nutrient recycling. *Current trends in microbial biotechnology for sustainable agriculture*, 1-21.

2. Costa, O. Y., Raaijmakers, J. M., &Kuramae, E. E. (2018). Microbial extracellular polymeric substances: ecological function and impact on soil aggregation. *Frontiers in microbiology*, *9*, 1636.

3. Bhantana, P., Rana, M. S., Sun, X. C., Moussa, M. G., Saleem, M. H., Syaifudin, M., ... & Hu, C. X. (2021). Arbuscular mycorrhizal fungi and its major role in plant growth, zinc nutrition, phosphorous regulation and phytoremediation. *Symbiosis*, *84*, 19-37.

4. Hamilton, A. J., Burry, K., Mok, H. F., Barker, S. F., Grove, J. R., & Williamson, V. G. (2014). Give peas a chance? Urban agriculture in developing countries. A review. *Agronomy for sustainable development*, *34*, 45-73.

5. Haughey, E. (2021). Climate change and land use in Ireland. *Wexford: Environmental Protection Agency*.

6. Sabir, M. S., Shahzadi, F., Ali, F., Shakeela, Q., Niaz, Z., & Ahmed, S. (2021). Comparative effect of fertilization practices on soil microbial diversity and activity: an overview. *Current Microbiology*, *78*, 3644-3655.

7. Pankievicz, V., Irving, T. B., Maia, L. G., &Ané, J. M. (2019). Are we there yet? The long walk towards the development of efficient symbiotic associations between nitrogen-fixing bacteria and non-leguminous crops. *BMC biology*, *17*(1), 1-17.

8. Sabir, M. S., Shahzadi, F., Ali, F., Shakeela, Q., Niaz, Z., & Ahmed, S. (2021). Comparative effect of fertilization practices on soil microbial diversity and activity: an overview. *Current Microbiology*, *78*, 3644-3655.

9. Mitra, D., Mondal, R., Khoshru, B., Senapati, A., Radha, T. K., Mahakur, B., ... & MOHAPATRA, P. K. D. (2022). Actinobacteria-enhanced plant growth, nutrient acquisition, and crop protection: Advances in soil, plant, and microbial multifactorial interactions. *Pedosphere*, *32*(1), 149-170.

10. Sharma, M., Dangi, P., & Choudhary, M. (2014). Actinomycetes: source, identification, and their applications. *International Journal of Current Microbiology and Applied Sciences*, *3*(2), 801-832.

11. 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.

12. Jayaraman, S., Naorem, A. K., Lal, R., Dalal, R. C., Sinha, N. K., Patra, A. K., & Chaudhari, S. K. (2021). Disease-suppressive soils—beyond food production: a critical review. *Journal of Soil Science and Plant Nutrition*, *21*, 1437-1465.

13. Tarafdar, J. C. (2022). Role of soil biology on soil health for sustainable agricultural production. In *Structure and Functions of Pedosphere* (pp. 67-81). Singapore: Springer Nature Singapore.

14. Mohammadi, K., Khalesro, S., Sohrabi, Y., & Heidari, G. (2011). A review: beneficial effects of the mycorrhizal fungi for plant growth. *J. Appl. Environ. Biol. Sci*, *1*(9), 310-319.

15. Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chemical fertilizers and their impact on soil health. *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs*, 1-20.

16. Osman, K. T., & Osman, K. T. (2013). Plant nutrients and soil fertility management. *Soils: principles, properties and management*, 129-159.

17. Kumar, A., & Dubey, A. (2020). Rhizosphere microbiome: Engineering bacterial competitiveness for enhancing crop production. *Journal of Advanced Research*, *24*, 337-352.

18. Mayer, M., Prescott, C. E., Abaker, W. E., Augusto, L., Cécillon, L., Ferreira, G. W., ... & Vesterdal, L. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *Forest Ecology and Management*, *466*, 118127.

19. Mayer, M., Prescott, C. E., Abaker, W. E., Augusto, L., Cécillon, L., Ferreira, G. W., ... & Vesterdal, L. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *Forest Ecology and Management*, *466*, 118127.

20. Cui, X., Zhang, Y., Gao, J., Peng, F., & Gao, P. (2018). Long-term combined application of manure and chemical fertilizer sustained higher nutrient status and rhizospheric bacterial diversity in reddish paddy soil of Central South China. *Scientific reports*, *8*(1), 16554.

21. Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for sustainable development*, *35*(3), 869-890.

22. Tripathi, S., Srivastava, P., Devi, R. S., &Bhadouria, R. (2020). Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In *Agrochemicals detection, treatment and remediation* (pp. 25-54). Butterworth-Heinemann.

23. Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A. N., Oh, J., ... & Dijkstra, J. (2013). SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *Journal of animal science*, *91*(11), 5070-5094.

24. Rivero, R. M., Mittler, R., Blumwald, E., &Zandalinas, S. I. (2022). Developing climate- resilient crops: improving plant tolerance to stress combination. *The Plant Journal*, *109*(2), 373-389.

25. Benbow, M. E., Barton, P. S., Ulyshen, M. D., Beasley, J. C., DeVault, T. L., Strickland, M. S., ... & Pechal, J. L. (2019). Necrobiome framework for bridging decomposition ecology of autotrophically and heterotrophically derived organic matter. *Ecological Monographs*, *89*(1), e01331.

26. Jayaraman, S., Naorem, A. K., Lal, R., Dalal, R. C., Sinha, N. K., Patra, A. K., & Chaudhari, S. K. (2021). Disease-suppressive soils—beyond food production: a critical review. *Journal of Soil Science and Plant Nutrition, 21*, 1437-1465.

27. Tripathi, S., Srivastava, P., Devi, R. S., &Bhadouria, R. (2020). Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In *Agrochemicals detection, treatment and remediation* (pp. 25-54). Butterworth-Heinemann.

28. Bassin, J. P., Castro, F. D., Valério, R. R., Santiago, E. P., Lemos, F. R., & Bassin, I. D. (2021). The impact of wastewater treatment plants on global climate change. In *Water conservation in the era of global climate change* (pp. 367-410). Elsevier.

29. Neher, D. A. (2010). Ecology of plant and free-living nematodes in natural and agricultural soil. *Annual review of phytopathology*, *48*, 371-394.

30. Yang, W., Li, C., Wang, S., Zhou, B., Mao, Y., Rensing, C., & Xing, S. (2021). Influence of biochar and biochar-based fertilizer on yield, quality of tea and microbial community in an acid tea orchard soil. *Applied Soil Ecology*, *166*, 104005.
31. Ye, S., Zeng, G., Wu, H., Liang, J., Zhang, C., Dai, J., ... & Yu, J. (2019). The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil. *Resources, Conservation and Recycling*, *140*, 278-285.
32. Pearsons, K. A., & Tooker, J. F. (2017). In-field habitat management to optimize pest control of novel soil communities in agroecosystems. *Insects*, *8*(3), 82.
33. Gu, Y., Wei, Z., Wang, X., Friman, V. P., Huang, J., Wang, X., ... &Jousset, A. (2016). Pathogen invasion indirectly changes the composition of soil microbiome via shifts in root exudation profile. *Biology and Fertility of Soils*, *52*, 997-1005.
34. Zwolak, A., Sarzyńska, M., Szpyrka, E., &Stawarczyk, K. (2019). Sources of soil pollution by heavy metals and their accumulation in vegetables: A review. *Water, air, & soil pollution*, *230*, 1-9.
35. Abdu, N., Abdullahi, A. A., & Abdulkadir, A. (2017). Heavy metals and soil microbes. *Environmental chemistry letters*, *15*, 65-84.
36. Mathesius, U. (2022). Are legumes different? Origins and consequences of evolving nitrogen fixing symbioses. *Journal of Plant Physiology*, 153765.
37. Yang, T., Siddique, K. H., & Liu, K. (2020). Cropping systems in agriculture and their impact on soil health-A review. *Global Ecology and Conservation*, *23*, e01118.
38. Miransari, M. (2011). Soil microbes and plant fertilization. *Applied microbiology and biotechnology*, *92*, 875-885.
39. Hodge, A., & Fitter, A. H. (2013). Microbial mediation of plant competition and community structure. *Functional Ecology*, *27*(4), 865-875.
40. Shah, A. M., Khan, I. M., Shah, T. I., Bangroo, S. A., Kirmani, N. A., Nazir, S., ... & Biswas, A. (2022). Soil microbiome: a treasure trove for soil health sustainability under changing climate. *Land*, *11*(11), 1887.
41. El Mountassir, G., Minto, J. M., van Paassen, L. A., Salifu, E., & Lunn, R. J. (2018). Applications of microbial processes in geotechnical engineering. *Advances in applied microbiology*, *104*, 39-91.
42. Römheld, V. (2012). Diagnosis of deficiency and toxicity of nutrients. In *Marschner's mineral nutrition of higher plants* (pp. 299-312). Academic press.
43. Dallas, J. W., & Warne, R. W. (2023). Captivity and animal microbiomes: potential roles of microbiota for influencing animal conservation. *Microbial ecology*, *85*(3), 820-838.
44. Jat, M. L., Dagar, J. C., Sapkota, T. B., Govaerts, B., Ridaura, S. L., Saharawat, Y. S., ... & Stirling, C. (2016). Climate change and agriculture: adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. *Advances in agronomy*, *137*, 127-235.