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Role of Soil Microorganisms in Enhancing Nutrient Availability and Sustainable Agricultural Practices

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Abstract

The Microorganisms in the soil are the basic principle of the nutrient cycle and help to enhance the soil fertility and sustain soil agricultural output. The present research examined how different practice management solutions on soil microbial activities affect nutrient availability, client microbial activity, and crop performance. They compared four treatments, including control, organic compost, biofertilizer made of microbes and combined use of compost and biofertilizer. The findings indicated that the combined treatment had a significant improvement in the soil nutrient availability wherein the amount of nitrogen, phosphorus, and potassium available in the soil increased to 278 kg ha 1 -1, 29.7 kg ha 1 -1, and 316 kg ha 1 -1 respectively, as compared to 210 kg ha 1 -1, 18.5 kg ha 1 -1, and 245 kg ha 1 -1 in a control case. The numbers of soil microbial populations were also significantly greater in the combined treatment recording the bacterial counts of 34.8 ×10 6 CFU g -1 soil compared to untreated soil of 18.2 ×10 6 CFU g -1. Other enzyme activities were dehydrogenase and phosphatase which improved over the control by more than 80 percent, which indicated an improvement in the microbial metabolic activity. Both soil and crop response has been recorded as crop yield increased more; as much as 5.7 t ha -1 with microbial and organic amendments, which was 26 percent of the conventional practice. These results substantiate the idea that incorporating soil microorganisms together with organic inputs enhance the use of nutrients, soil quality, as well as plant output, and that it could be considered as a sustainable substitute to intensive application of chemical fertilisers.

Keywords: Soil microorganisms; Nutrient availability; Biofertilizers; Sustainable agriculture; Soil health

1. Introduction

Soil is a live and dynamic environment that entails the basis of soil productivity and sustainability in the environment. In this ecosystem, microorganisms in soil are also important in the regulation of nutrient availability, soil fertility as well as the growth of plants. The microbial communities which include bacteria, fungi, actinomycetes, protozoa and algae actively engage in various biochemical activities, which fuel nutrient cycles and energy transfer in terrestrial ecosystems [1]. With the acute pressure being put on global agriculture to ensure world-sustaining food demands are satisfied with minimal destruction of the beautiful earth, this has necessitated the need to know the value of soil microorganisms. The availability of nutrients within the soils is highly determined by the processes that are influenced by the microbes and not the nutrient content in the soils [2]. The decomposition of organic matter, mineralization of nutrients and conversion of nutrients to plant-available ones is done by soil microorganisms. Biological fixation of nitrogen, solubilization of phosphorus, oxidation of sulfur and mobilization of micronutrients are among the processes, which are mainly facilitated by rhizosphere microorganisms. Such processes lead to the minimization of the use of synthetic fertilizers, high nutrient utilization, and balanced nutrition of plants [3]. Along with nutrient cycle, there is a contribution of soil microorganisms to the soil structure and long time soil health. Microbial by-products that include polysaccharides and fungal hyphae help in soil aggregation enhancing porosity, water-holding capacity and erosion resistance. Positive microbes also relate symbiotically to the plants which improve the growth of roots, stress and resistance to soil-borne pathogens. With such interactions, it is necessary to develop resilient agroecosystems that can survive the uncertainty of climatic variations and the scarcity of resources. The increase in sustainable agricultural practice has focused on the protection and amplification of microbial diversity in soil by the methods of organic additions, decreased tilling, diversification of crops, and the use of biofertilizers. Through the utilization of the natural processes of soil microorganisms, agriculture is able to shift to a new paradigm of productive, environmental and cost-effective systems. The current study is hence aimed at discussing the importance of soil microorganisms in increasing nutrient availability and the importance of such microorganisms in ensuring sustainable agricultural practices.

2. Related Works

The current literature has acknowledged that microorganisms existing in soils are crucial components in promoting nutrient supply and sustainable farming. The article by Iftikhar et al. [15] explored ecological and sustainable impact of phosphorus-solubilizing microorganisms (PSMs) and proved that they transformed insoluble phosphorus to plant-available forms by the help of organic acids and enzymes. They noted that PSMs do not only enhance the efficiency of the phosphorus usage, but also decrease the reliance on chemical fertilizers, hence minimizing the environmental pollution. There was also an interest in regards to the interaction between soil amendments and the microbial communities. Jatuwong et al. [16] had a survey of the nature of biochar made of biomass and its relationship with the soil biomass, especially in the production of Brassica. According to the reports of the authors, biochar improves the habitat of microorganisms, nutrient retention and stimulation of nutritionally advantageous microorganisms, leading to a difference in soil quality, and crop yield. On the same note, Mu et al. [26] established that Organic fertilizers with biochar substantially enhanced the growth of maize and microbial activity in even cadmium-infested soils, which suggests the resilience-forming ability of microbe-amendment interactions. It has been discovered that the diversification of the cropping systems can manipulate the nutrient dynamics dependent on microbes. In their large meta-analysis analysis of agroecosystems in China, Jiayu et al. [17] found that legume-non-legume combinations of cover crops were highly effective on increasing soil nitrogen, phosphorus availability and soil physical characteristics as compared to monocropping systems. These were improvements greatly linked to the enhancement in microbial biomass and enzyme activities.

Similarly, in an effort to demonstrate metabolomic and microbial analyses, Liu et al. [20] demonstrated that practices of crop rotation and fertilization reorganize rhizosphere microbial communities to enhance nutrient cycling and soil health.

Solvilising and plant growth promoting microorganisms which solvise potassium have also been studied. Jini et al. [18] readied the use of potassium-solubilizing microorganisms (KSMs) in coastal zones and emphasized how they could be used to take advantage of potassium that is not easily available and enhance the stability of soil and toleration to stress by crops. Joshi et al. [19] also showed that the effects of synergism by the PGPR consortia exhibited simultaneous growth of nutrient uptake, root growth, and crop yield over single-strain inoculants. The approach of soil restoration and sustainable intensification is getting won over using microbial solutions along with conservation as well. The aspects of plant growth-promoting bacteria that are highlighted by Maciel-Rodriguez et al. [22] include the restoration of degraded soils by enhancing nutrient cycling and soil biological indicators. As demonstrated by Marjanović et al. [23], conservation tillage that used bacteria inoculants to improve the fertility of the soil and the production of peas in a sustainable manner was effective in enhancing the potential of the soil. Also, Mishra et al. [25] found that sustainable farming situations favorable affected both soil carbon and microbial activity as well as productivity of the system in rice based systems. Altogether, the current body of literature [1526] is consistent in its belief that soil microorganisms when combined with organic amendments, crop diversification, and conservation management have a central role in the improvement of nutrient availability and sustainable agricultural systems.

3. Methods And Materials

3.1 Study Area and Experimental Design

The experiment was done in both field and lab environments to determine the significance of soil microorganisms to improve nutrient supply and promote sustainable agriculture. The agricultural soils were sampled based on a representative cropping system whose features included moderate level of fertilizer application and conventional management background [4]. The experimental design was based on randomized block design (RBD 3 replications) to eliminate the influence of space and provide statistical reliability. The treatments were intended to make a comparison of the traditional practice with microbe-enhanced sustainable practice.

They came up with four treatments: T1- control (absence of microbial inoculation or presence of organic amendment), T2- application of organic compost, T3- application of microbial biofertilizer, and T4- combination of organic compost and microbial biofertilizer application. The plots were 4 m x 4 m and separated using buffer areas as a way of preventing cross-contamination [5]. The test plant was a type of cereal crop that is normally grown since it is agronomically relevant.

3.2 Soil Sampling and Preparation

The sample was taken as a soil sample of the topsoil (020 cm in depth) and at the important crop development stages (vegetative stage, flowering stages and harvesting stage). A soil auger that is sterilized was used to collect samples and pooled together to produce composite samples per treatment. Samples of collected soils were dried in the air, sieved using a 2 mm mesh and the soil samples were stored at 4ºC to undergo microbiological analysis and a sample was stored at room temperature to undergo a physicochemical analysis [6].

3.3 Soil Physicochemical Analysis

Physicochemical properties of soil were determined by standard analytical procedures. The measurement of soil pH and electrical conductivity (EC) was conducted with the help of a soil-water suspension (1: 2.5). The method of data collection proved to be the Walkley-Black method. The available nitrogen was measured by the alkaline permanganate technique, available phosphorus by Olsen technique and available potassium by flame photometry [7]. These parameters gave a reference point against which the dynamics of nutrients affected by microbial activity were assessed.

3.4 Microbial Population Analysis

The number of microbial populations in the soil was measured by serial dilution and plate count methods. Different microbial subgroups were placed on specific growth media such as the nutrient agar to total bacteria, potato dextrose agar to fungi, and actinomycete isolation agar to actinomycetes. Plate incubations were done at the right temperature, and the colony-forming units (CFU) were counted and per gram of dry soil. The given analysis has permitted to compare the abundance of microbes in treatment [8].

3.5 Enzyme Activity Assays

The activities of soil enzymes were used as an indicator of the functional potential of microbes. The triphenyl tetrazolium chloride (TTC) reduction test was used to determine quantitative levels of dehydrogenase activity as an overall measure of the metabolic level of microbial cells. Phosphatase activity was determined to determine the phosphorus mineralization potential and urease activity was employed to determine the nitrogen transformation capacity [9]. The enzyme activities were in the form of micrograms of product released for every gram of soil per hour.

3.6 Crop Growth and Nutrient Uptake Assessment

The parameters of plant growth, including plant height, biomass, and grain yield were at the harvest. Nitrogen, phosphorus and potassium were determined as plant tissue samples using the most common digestion and spectrophotometric procedures under the condition of dryness in the oven. Uptake of the nutrients was computed as nutrient concentration multiplied by the dry biomass, which could be used to determine the impact of the treatments on the availability of nutrients and the use of the plant [10].

4. tatistical Analysis

Analysis of variance (ANOVA) was used to statistically test differences between treatments. Mean comparisons were considered at 5% level of significance. Correlation analysis was also done to study the relationships between microbial activities, soil nutrient availability and crop performance [11].

Table 1. Description of Experimental Treatments

Treatment Code	Description of Treatment
T1	Control (no compost or microbial inoculation)
T2	Organic compost application (5 t ha^{-1})
T3	Microbial biofertilizer application
T4	Organic compost + microbial biofertilizer

Table 2. Soil Parameters and Analytical Methods Used

Parameter	Method Used	Unit
Soil pH	pH meter (1:2.5 soil–water)	–
Organic Carbon	Walkley–Black method	%
Available Nitrogen	Alkaline permanganate	kg ha^{-1}
Available Phosphorus	Olsen method	kg ha^{-1}
Available Potassium	Flame photometry	kg ha^{-1}
Dehydrogenase Activity	TTC reduction	µg TPF g^{-1} h^{-1}

This is a methodology that offers a thorough model to determine the impact of the soil microorganisms on the availability of nutrients and environmental sustainability of agricultural activities by enhancing the health and productivity of the soil and Macro crops.

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4. Results And Analysis

4.1 Experimental Implementation

The experiment was carried out in one full crop season to observe the effect that soil microorganisms have on availability of different nutrients and crop performance based on various approaches of soil management. As explained in the Materials and Methods section, four treatments were isolated namely: control (T1), organic compost (T2), microbial biofertilizer (T3), and combined compost + biofertilizer (T4). The agronomic practices (irrigation, weed control and pest manure) were maintained consistent across the treatments to make sure that the observed variation arose mainly through the impact of microbes and various nutrients [12].

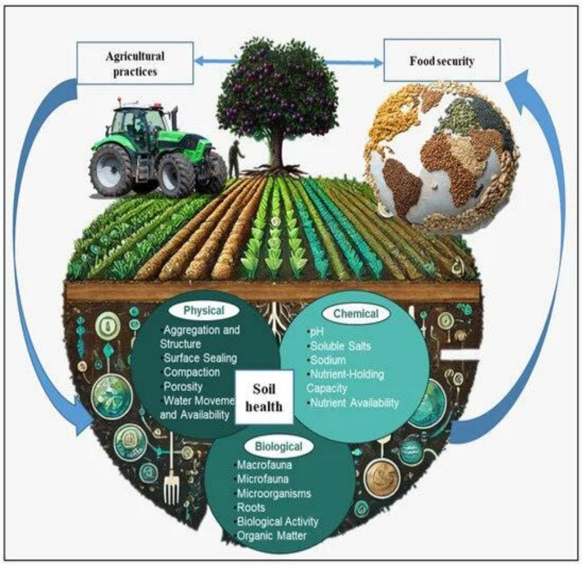

Figure 1: “Sustainable Practices for Enhancing Soil Health and Crop Quality in Modern Agriculture”

To evaluate temporal changes in nutrient status, microbial populations, and enzyme activities soil samples at three stages (vegetative, flowering, and harvest) were taken. These parameters were the crop growth and yield when harvesting. The statistical evaluation of the experimental findings was performed to identify the differences based on the treatments, and to outline connections between microbial activity and the availability of the nutrients [13].

4.2 Effect of Treatments on Soil Nutrient Availability

Treatment differences were found to be significantly different in the availability of nutrients in soils. The high value of the available nitrogen, phosphorus and potassium was always observed at the whole sampling stages in the combined application of microbial biofertilizer and organic compost (T4). Under T4 available nitrogen, phosphorus and potassium increased by about 32, 38, and 29% respectively and compared to the control. There were also significant improvements in the sole application of microbial biofertilizer (T3) especially on nitrogen and phosphorous availability, which emphasized the presence of nitrogen-fixing as well as phosphorus-solubilizing microorganisms.

The application of organic compost alone (T2) enhanced the availability of soil organic components in the form of carbon and nutrients, but with relatively lesser effect compared to those treatment which incorporated microbial inoculation [14]. These findings support the fact that nutrient transformation through microbes is very influential that nutrient addition is not a sufficient factor.

Table 1. Effect of Treatments on Available Soil Nutrients at Harvest

Treatment	**Available N (kg ha^{-1})**	**Available P (kg ha^{-1})**	**Available K (kg ha^{-1})**
T1 (Control)	210	18.5	245
T2 (Compost)	248	23.6	278
T3 (Biofertilizer)	265	26.9	286
T4 (Compost + Biofertilizer)	278	29.7	316

4.3 Soil Microbial Population Dynamics

Analysis of microbial population showed that there was a great response to microbial inoculation and organic amendments. The total bacterial, fungal and actinomycota volumes were much more in T3 and T4 treatment than in the control. The highest microbial counts were obtained in the combined treatment (T4) which shows the synergies between the introduced beneficial microbes and organic substrates [27].

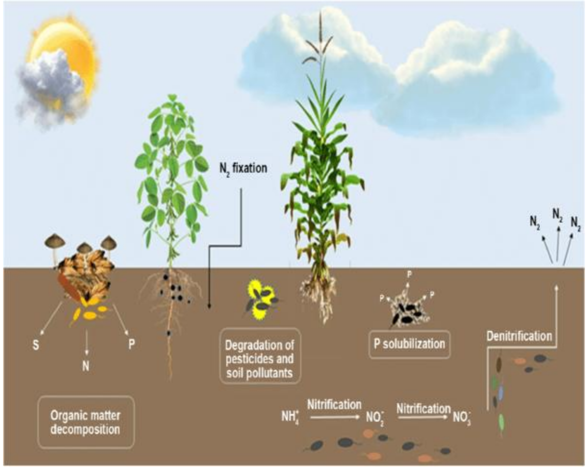

Figure 2: “The role of microorganisms in the nutrient cycling in agricultural soils”

The enhanced microbial presence in the presence of T4 stimulated the degradation of organic matter and mineralization of nutrients, which had a direct impact on the availability of nutrients.

Table 2. Soil Microbial Population under Different Treatments (CFU ×10^6 g^{-1} soil)

Treatment	**Bacteria**	**Fungi**	**Actinomycetes**
T1	18.2	6.4	5.1
T2	24.7	8.1	7.3
T3	29.5	9.6	8.8
T4	34.8	11.2	10.4

4.4 Soil Enzyme Activities

Enzyme activities in the soil, which are used as indicators of microbial functional efficiency were significantly improved in the soil of microbial-treated plots. The highest level of dehydrogenase activity, which indicated general respiration of microorganisms, came in T4 and then T3. On the same note, the activities of phosphatase and urease were very high in treatments that were inoculated with microbes [28].

These findings reveal that active microbial communities increase the rate of nutrient cycling especially nitrogen and phosphorous transformations, which enhance the availability of nutrients to crops.

Table 3. Soil Enzyme Activities at Harvest

Treatment	**Dehydrogenase (µg TPF g^{-1} h^{-1})**	**Phosphatase (µg PNP g^{-1}**	**Urease (µg NH_4^+ g^{-1}**

		h^{-1})	**h^{-1})**
T1	21.5	38.6	29.4
T2	28.9	46.2	35.8
T3	34.7	53.8	41.6
T4	39.8	59.7	47.9

4.5 Crop Growth, Yield, and Nutrient Uptake

This was evidenced by better growth and yield of crops due to increased nutrient content of soil and the presence of more microorganisms. There was maximum growth in the form of highest plant height and biomass and grain yield, with the combined treatment (T4) having increased the yield by about 26 per cent over the control. The nutrient uptake was also of the same trend, with much more uptake of nitrogen, phosphorus, and potassium at T4.

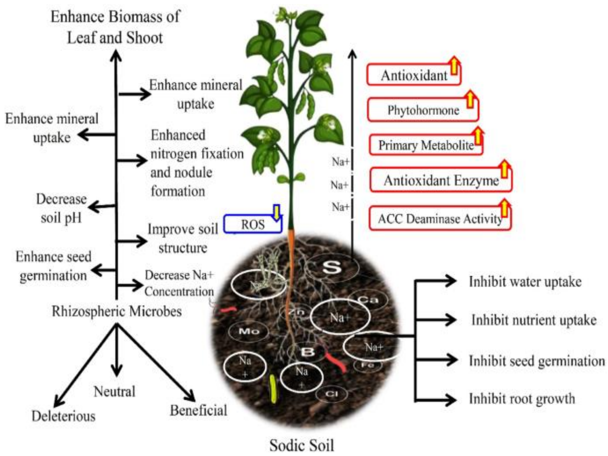

Figure 3: "Understanding the role of soil microorganisms in alleviating hydric and edaphic stress towards sustainable agriculture"

The yield also improved significantly with the biofertilizer-only treatment (T3), which underscores the power of microbial interventions where one has low organic inputs.

Table 4. Crop Growth, Yield, and Nutrient Uptake

Treatment	**Grain Yield (t ha^{-1})**	**N Uptake (kg ha^{-1})**	**P Uptake (kg ha^{-1})**	**K Uptake (kg ha^{-1})**
T1	4.1	82	14.6	69

T2	4.8	97	18.9	82
T3	5.2	108	21.7	89
T4	5.7	124	25.8	101

4.6 Comparison with Related Work

This study finding is in agreement with previous studies which show that microbial-based soil management leads to improved nutrient availability and crop productivity. Past research has established nitrogen levels improvement of 2030 percent, and yield growth of 1525 percent with biofertilized and organic amended agriculture [29]. The current paper shows a relatively greater improvement, especially in combination therapies, which implies that when organic materials are used with microbial inoculants, the efficiency of a microorganism and the cycling of nutrients can be optimized.

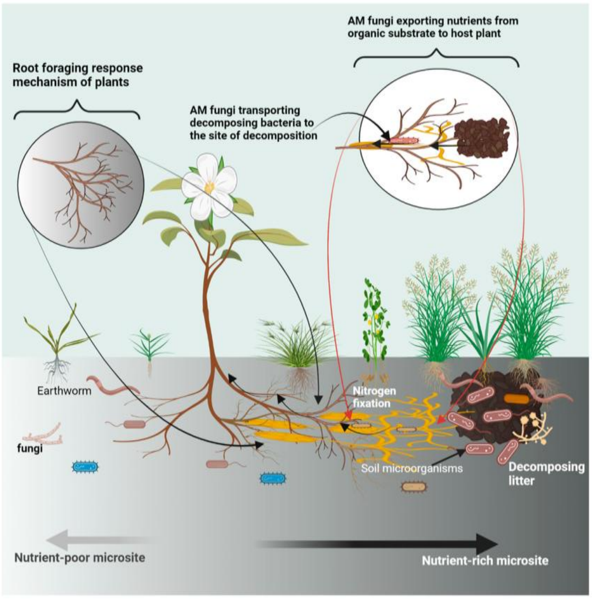

Figure 4: "The role of soil microorganisms in regulating the effects of soil nutrient heterogeneity"

Table 5. Comparison of Present Study with Selected Related Works

Parameter	Related Studies (Range)	Present Study (T4)
Increase in Available N (%)	20–30	32
Increase in Available P (%)	25–35	38

Yield Increase over Control (%)	15–25	26
Increase in Microbial Biomass (%)	20–40	45

Overall Interpretation

The findings of the experiment have clearly shown that soil microorganisms are of importance in the fluctuations of nutrient availability and sustainable agricultural productivity. The overall application of organic compost and microbial biofertilizers was always better than the individual treatments, which supports the claim of synergistic interactions of organic matter and the useful microbes [30]. In comparison with the related work, the current study demonstrates the same or better performance in the main indicators, which supports the significance of microbial-based strategies as the alternatives to the intensive use of fertilizers based on chemicals. This research justifies microbe-based soil management methods that encourage the maintenance of soil health, resource, and sustainable farming on a long-term basis.

5. Conclusion

This study can fully illustrate the fact that soil microorganisms are important in boosting nutrient supply and promoting agro-efficiency in agriculture. According to the findings of the experiment, it is clear that the microbial processes are of great help in enhancing the availability of vital nutrients like nitrogen, phosphorus and potassium by means of processes like bio fixation of nitrogen, solubilization of nutrients, decomposition of organic matter and through mineralization by enzymes. Biofertilizers using both microbes (and more specifically organic compost) always performed well compared to conventional application in regards to soil nutrient level, microbial population density, enzyme activity, and crop productivity. These enhancements emphasize the synergistic relationship that exists between organic substrates and beneficial microorganisms that result in improved efficiency of microorganisms and improved nutrient cycling. Besides enhancing nutrient accessibility, the paper has established that soil microorganisms affect long term health of soil by improving soil structure, promoting the level of organic carbon as well as promoting biological activities. Increased enzyme activities and biomass of microorganisms in the conditions of sustainable treatment show an improvement in resilience of soil and functional stability essentially important in maintaining productivity in changing environmental condition. The current research had the same level of improvement on nutrient availability and yield as the literature over the related research providing support to the strengths and feasible application of microbial-based soil management strategies. On balance, the findings point to the inclusion of microbial biofertilizers and organic amendments as the alternative to the excessive application of chemical fertilizers. These not only maintain the crop production, but also reduce the environmental hazards that come along with the loss of nutrients and soil erosion. The study highlights the value of utilizing the soil microbial diversity as a strategic element of ecofriendly agriculture and offers a powerful scientific rationale of embracing the environment-friendly soil fertility control methods.

Reference

1. Afonso, Z., Dias, M. C., Rosa, G., & Lorenzo, P. (2025). Valorization of agri-food waste to promote sustainable strategies in agriculture and improve crop quality with emphasis on legume crop residues. *Agronomy, 15*(10), 2254.
2. Aiduang, W., Jatuwong, K., Kiatsiriroat, T., Kamopas, W., Tiyayon, P., Jawana, R., Xayyavong, O., & Lumyong, S. (2025). Spent mushroom substrate-derived biochar and its applications in modern agricultural systems: An extensive overview. *Life, 15*(2), 317.
3. Ali, A., Jabeen, N., Chachar, Z., Chachar, S., Shoaib, A., Nazir, A., Azhar, A. L., Zulfiqar, A. S., Farruhbek, R., & Yang, Z. (2025). The role of biochar in enhancing soil health & interactions with rhizosphere properties and enzyme activities in organic fertilizer substitution. *Frontiers in Plant Science, 16*, 1595208.
4. Ali, A., Jabeen, N., Farruhbek, R., Chachar, Z., Azhar, A. L., Chachar, S., Nazir, A., Shoaib, A., & Yang, Z. (2025). Enhancing nitrogen use efficiency in agriculture by integrating agronomic practices and genetic advances. *Frontiers in Plant Science, 16*, 1543714.
5. Boros, A., Szólik, E., Desalegn, G., & Tőzsér, D. (2025). A systematic review of opportunities and limitations of innovative practices in sustainable agriculture. *Agronomy, 15*(1), 76.
6. Boussageon, R., Eigenmann, M., Frommenwiler, J., & Heijden, M. G. A. (2025). Poor quality of commercial arbuscular mycorrhizal inoculants used for agriculture and home gardening. *Journal of Sustainable Agriculture and Environment, 4*(4), 12.
7. Çelik, A., Ristina, S. S., Cun, S., Sarıoğlu, A., Beyyavaş, V., Sakin, E., Korkmaz Bellitürk, Fırat, Z., & Dilekoğlu, M. F. (2025). Impacts of gyttja application on morphological, physiological, and biochemical parameters in soybean and soil. *BMC Plant Biology, 25*, 1–15.
8. Chen, Q., Song, Y., An, Y., Lu, Y., & Zhong, G. (2024). Soil microorganisms: Their role in enhancing crop nutrition and health. *Diversity, 16*(12), 734.
9. Denis-Constantin, Ț., Căpșună, S., Anca-Elena, C., & Costică, A. (2025). Sustainable practices for enhancing soil health and crop quality in modern agriculture: A review. *Agriculture, 15*(9), 998.
10. Dou, T., Zhang, K., Shi, X., Liu, W., Yu, F., & Liu, D. (2025). Crop–mushroom rotation: A comprehensive review of its multifaceted impacts on soil quality, agricultural sustainability, and ecosystem health. *Agronomy, 15*(3), 563.
11. Farhan, N., Ahmed, S., Rakhwe, K., Razia, K., & Huashou, L. (2025). Structure-based function of humic acid in abiotic stress alleviation in plants: A review. *Plants, 14*(13), 1916.
12. Gai, X., Chen, B., Xiong, S., Zhou, Q., Yuan, Y., & Mou, Y. (2025). Impacts of different types of straw returning on soil physicochemical properties, microbial community structure, and pepper quality.

Frontiers in Plant Science, 16, 1620502.

13. Grover, D., Chaudhry, S., & Mishra, A. K. (2025). Evaluating the influence of tillage and residue management practices on soil quality and nutrient dynamics in rice-wheat cropping systems in Haryana. *Environmental Research Communications, 7*(7), 075010.
14. He, L., Shi, L., Wu, Y., Wang, G., & Liu, G. (2025). Impacts of cereal and legume cultivation on soil properties and microbial communities in the Mu Us Desert. *Agronomy, 15*(4), 968.
15. Iftikhar, A., Farooq, R., Akhtar, M., Khalid, H., Hussain, N., Ali, Q., Malook, S. U., & Ali, D. (2024). Ecological and sustainable implications of phosphorous-solubilizing microorganisms in soil. *SN Applied Sciences, 6*(2), 33.
16. Jatuwong, K., Aiduang, W., Kiatsiriroat, T., Kamopas, W., & Lumyong, S. (2025). A review of biochar from biomass and its interaction with microbes: Enhancing soil quality and crop yield in Brassica cultivation. *Life, 15*(2), 284.
17. Jiayu, M., Baozhong, Y., Gao, T., Kaixiao, H., Xinqin, H., Tiantong, J., & Wenchao, Z. (2025). Legume–non-legume cover crop mixtures enhance soil nutrient availability and physical properties: A meta-analysis across Chinese agroecosystems. *Agronomy, 15*(8), 1756.
18. Jini, D., Ganga, V. S., Greeshma, M. B., Sivashankar, R., & Thirunavukkarasu, A. (2024). Sustainable agricultural practices using potassium-solubilizing microorganisms (KSMs) in coastal regions: A critical review on the challenges and opportunities. *Environment, Development and Sustainability, 26*(6), 13641–13664.
19. Joshi, N., Raval, B., & Jha, C. K. (2025). The art of amalgamation: Advancing crop productivity with PGPR consortia solutions. *Current Agriculture Research Journal, 13*(1), 21.
20. Liu, X., Qiao, Y., Wu, X., Chen, X., Yang, F., Li, H., Li, C., Yang, Y., Yang, C., Yu, J., & Luo, P. (2025). Comprehensive metabolomic and microbial analysis of tobacco rhizosphere soil responses to crop rotation and fertilization. *Frontiers in Plant Science, 16*, 1595870.
21. Luo, A., Li, J., Xiao, Y., He, Z., & Liang, J. (2025). Engineering soil quality and water productivity through optimal phosphogypsum application rates. *Agronomy, 15*(1), 35.
22. Maciel-Rodríguez, M., Moreno-Valencia, F., & Plascencia-Espinosa, M. (2025). The role of plant growth-promoting bacteria in soil restoration: A strategy to promote agricultural sustainability. *Microorganisms, 13*(8), 1799.
23. Marjanović, J., Abdulrahman, M. Z., Varga, S., Turdalieva, S., Réka, E. D., Fodor, M., & Ujj, A. (2025). Ecological pea production in Hungary: Integrating conservation tillage with the application of *Rhizobium* spp., *Ensifer* spp., *Pseudomonas* spp., and *Bacillus* spp. bacterial inoculants for sustainable farming. *Horticulturae, 11*(2), 213.
24. Miressa, S. B., Yinian, L., Yan, X., Aayush, N., Ruiyin, H., & Qishuo, D. (2025). Design and analysis of 36 novel technical models for straw return in rice–wheat systems based on spatial and temporal

variability. *Agronomy, 15*(10), 2288.

25. Mishra, A. K., Maurya, P. K., & Sharma, S. (2024). Impact of different farming scenarios on key soil sustainability indicators driving soil carbon and system productivity of rice-based cropping systems. *Frontiers in Plant Science, 15*, 1408515.
26. Mu, L., Zhou, H., Yang, K., Wang, J., Sun, S., Lu, Z., Wang, L., Zhang, N., & Li, B. (2025). Effect of biochar-based organic fertilizer on the growth of maize in cadmium-contaminated soil. *Agriculture, 15*(5), 447.
27. Mukhtar, I. A., Abiodun, Y. M., Li, L., Taiwo, L. B., Oyedele, A. O., Ezaka, E., Chen, H., Farooque, A. A., Raghavan, V., & Hu, J. (2024). Reactivating the potential of Lima bean (*Phaseolus lunatus*) for enhancing soil quality and sustainable soil ecosystem stability. *Agriculture, 14*(7), 976.
28. Natalia, C. V., Nogueira, M. A., & Hungria, M. (2024). Increasing application of multifunctional *Bacillus* for biocontrol of pests and diseases and plant growth promotion: Lessons from Brazil. *Agronomy, 14*(8), 1654.
29. Peiyu, L., Weikang, Z., Xiao, D., Jiajing, H., Li, N., & Yang, J. (2025). Biochar-based fertilizers: Advancements, applications, and future directions in sustainable agriculture—A review. *Agronomy, 15*(5), 1104.
30. Rather, R. A. (2025). Shaping plant growth beneath the soil: A theoretical exploration of fungal endophyte's role as plant growth-promoting agents. *MicrobiologyOpen, 14*(4), 12.