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Research Article

The Role of Soil Microbiome in Sustainable Agriculture

Hauwa Hussaini., and Aminu .Yusuf. Fardami
[1]Department of Microbiology, Faculty of science. Sokoto State University.
[2] Department of Microbiology, Faculty of Natural Sciences Usumanu Danfodiyo University Sokoto
***Corresponding author's Email**: h_hauwa@yahoo.com doi.org/10.55639/607.special.005

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ABSTRACT

The soil environment is a natural habitat for many microbiomes They play a very crucial role in the sustenance of nutrient balance and ecosystem functioning. Authochtonous members of the soil community may persist for a million years and enhance soil fertility. the mycorrhizal fungi and rhizo-bacteria are both associated with the roots of some plants which trigger the formation of root nodules of legume plants soil microbiomes are found in association with plant through the intense network of plant–microbe interactions. They are found to play a vital role in nutrient cycling, the rhizo bacteria receive nutrients from the plant and produce nitrogen in a form that can be used by the plant for growth and fruit production. Mycorrhizal fungi also form associations with plants roots, where they provide the host plant with increased nutrient uptake from the soil and improved abiotic stress tolerance. These soil and plant associated microbes also play an important role in protection of plants from different plant pathogens by producing different secondary metabolites such as ammonia, hydrogen cyanide, siderophores, and hydrolytic enzymes. The soil microbiomes with plant growth-promoting (PGP) attributes have emerged as an important and promising tool for sustainable agriculture. Disease-causing bacteria or fungi can infect plants through the soil which will lead in large reductions in agricultural products..

Corresponding author: Hauwa Hussaini, **Email:** h_hauwa@yahoo.com
Department of Microbiology, Faculty of science. Sokoto State University

INTRODUCTION

Soil environment is a natural habitat for many microbiomes, but the major goal of soil microbiology is aimed at developing strategies for manipulating soil microbial communities to enhance crop productivity and sustainability agriculture. The soil is a vast dynamic and complex ecosystem concealing a diverse species of microbial consortium, which plays a significant role in agricultural practices and food sustainability. The most interesting aspect is in the use of microbial inoculants, biofertilizers, and organic amendments to promote beneficial microbes, the success of microbial inoculants, for example, depends on several factors including the compatibility of the introduced microbes with the existing soil community that is the authochtonous members, environmental conditions, and crop species. In many cases, the allochtonous species introduced fail to establish or persist in the soil, limiting their effectiveness. (QingXia, and Chen. 2024)

These soil flora and fauna have made a significant contribution that includes soil fertility, plant resilience, and agricultural sustainability. intensive agricultural practices can reduce microbial biodiversity, hence result in large loss of biodiversity, also impairing the soil's ability to support healthy crops in the long term.

The soil microbiome is made up of microorganisms that include soil flora and fauna (bacteria, fungi, archaea, viruses, and protozoa), where they interact with plant roots and the surrounding environment. This biological system influences many processes, such as:

Nutrient cycling in these process microbes decompose organic matter, improving the availability of micronutrients and other essential elements for plant growth. The functional diversity of soil microorganisms refers to the space in which plants grow, and soil plays a role in this function, which includes microbial activity and substrate metabolism (Yao, Z.W; et al., 2023). Soil microbial diversity, functional diversity is even more important because soil microorganisms are directly involved in material cycling and energy flow (Zhang, Y *et al*., 202). Soil microorganisms act as decomposers in the material cycle and energy flow, and their main function is to decompose organic matter, which can promote the decomposition of apoplastic materials and organic matter conversion. The species diversity of soil microorganisms leads to functional diversity. Soil microorganisms are of great help in the process of growing crops; for example, they promote the absorption of water and nutrient conversion between plants and soil, and the increase in soil fertility plays an important role in the growth of plants and crops such as through the decomposition of dead leaves by certain soil bacteria during their metabolism into organic soil for plant growth (Shah, F *et al.,* 2016). For example, specific nitrogen-fixing bacteria or mycorrhizal fungi play critical roles in nutrient cycling, which cannot be easily replaced by other microorganisms, Other examples include nitrogen fixation by rhizobia in legume root nodules and by actinomycetes in some non-legume root nodules (Thilakarathna, M.S. *et a*l., 2021; Booth, N.J *et al*., 2021), Arbuscular Mycorrhizal fungi (AM) may improve Phosphate nutrition, enhance Ntrate uptake, or improve disease resistance in their host plants. Other microbes, e.g. Nitrogen fixing bacteria or Phosphate solubilising bacteria, may synergistically interact with AM fungi and thereby benefit plant development and growth (Puppi G.Azcón Höflich G.(1994). Mycorrhizal fungi forming symbiotic associations between the root systems of some higher plants and fungi , and soil microorganisms being involved in the transformation of materials and energy flow in the soil, thus contributing to soil formation (Choreño-Parra, E.M *et al*., 2024).

Secondly, the functional diversity of soil microorganisms is also reflected in the solubilization of soil minerals. Research has shown that phosphorus-solubilizing bacteria can convert insoluble phosphorus into the available phosphate form, which can improve soil fertility and promote agricultural production (Tan, W.F.; *et al*., 2024].

However, the relationship between microbial diversity and ecosystem function is complex and context-dependent. While increased microbial richness and diversity are often associated with enhanced ecosystem functions, this relationship does not always hold true across all environments. Recent research indicates that the impact of microbial diversity on ecosystem function can vary based on environmental factors, functional redundancy, and the presence of specific important species for example, in systems with high functional redundancy, multiple microbial species may perform similar ecological roles, meaning that the loss of one or a few species may not significantly impact the overall ecosystem function (Louca, S *et al*., 2018). in systems with low redundancy, even minor reductions in diversity can lead to substantial declines in ecosystem performance. Moreover, certain functional species or groups can have a disproportionately large impact on ecosystem functions in comparison with overall diversity. In some cases, maintaining the presence of these key functional groups is more important for ecosystem stability than maximizing species richness.

In addition, soil microbial diversity also has significant impacts on plant microbiomes both above and below ground, which in turn influences plant health, resistance to pathogens, and overall productivity. Soil microbes can shape the composition of root-associated microbiomes by facilitating beneficial symbiotic relationships such as those involving mycorrhizal fungi and nitrogen-fixing bacteria, which improve nutrient uptake and plant growth (Primieri, S. *et al*., 2021). Additionally, soil microbial communities can influence the aboveground plant microbiome by modulating systemic plant defences and altering the release of volatile organic compounds, which can deter herbivorous insects (Pineda, A. *et al*., 2013).

Recent studies have highlighted that the soil microbial diversity can even affect the behaviour of herbivorous insects. by altering the plants' chemical profile through induced systemic resistance, soil microbes can make plants less attractive or more resistant to insect herbivory (Primieri, S. *et al*., 2021). For instance, beneficial microbes in the rhizosphere can trigger the production of secondary metabolites in plants, which act as deterrents to herbivores. These interactions demonstrate the far-reaching influence of soil microbial diversity on plant health and ecosystem stability, extending beyond nutrient cycling and soil structure to include impacts on plant-associated microbial communities and trophic interactions with herbivores. (Pineda, A.. *et al*., 2013).

PLANT MICROBE INTERACTION AND PLANT GROWTH PROMOTION

Certain groups of microorganisms are known to establish some positive symbiotic relationships with plants, stimulating the absorption of essential nutrients and development through the production of phytohormones and beneficial metabolites. better understanding of the interactions of soil microorganisms with each other and with plants is therefore crucial for the development of sustainable management of soil fertility and crop production.

The mycorrhizal symbiosis becomes even more important in sustainable agricultural systems where nutrient inputs are low. Under these circumstances Arbuscular Mycorrhizal mycelium (possibly in conjunction with bacteria or other fungi) could play an important role in nutrient mobilisation from crop residues. Hodge *et al*. (2001) demonstrated that the presence of the AM symbiont *Glomus hoi* enhanced decomposition of plant litter in soil and resulted in increased N capture from the litter . Hyphal growth of the fungal symbiont was also increased in the presence of the organic material. Bacteria associated with the AM can also assist in mobilising nutrients from soil, examples of this are available from bacterial-AM-legume tripartite symbiotic relationships, where diazotrophic bacteria provide fixed Nitrogen not only for the plant, but also for the fungus.

Arbuscular mycorrhizal symbiosis can also alleviate negative effects of plant pathogens and toxic levels of metals (Niemira B.A *et al*. (1996)]. In addition, the extraradical hyphae may interact with other soil organisms either indirectly by changing host plant physiology, including root physiology and patterns of exudation into the mycorrhizosphere, or directly by physically and/or metabolically interacting with other organisms in the mycorrhizosphere.

Different management strategies introduce different types of disturbances, which may influence microbial communities in various ways. Tillage causes a physical disruption of fungal mycelia and may change physicochemical properties of the soil. Crop rotation may cause a temporal disturbance in the presence of plant roots of a particular species.

Mixing of soil may negatively affect AM colonisation of plant roots, due to disruption of the extraradical mycelium, however, non-mycorrhizal fungi may also be affected. Excessive soil compaction can lead to reduced soil microbial biomass and enzyme activity with adverse implications for long-term soil health (Frankenberger W.T. Jr. and Dick W.A(1983). Since AM fungi may ameliorate the nutrient status of their hosts and provide protection against pathogens, it is possible that a low degree of tillage could be beneficial to AM colonisation and crop health. Conservation tillage (i.e., no tillage or less frequent tillage) tends to concentrate plant debris and consequently microbial biomass in the topsoil, and thus promotes survival of pathogens. The debris itself can provide an energy source available to the pathogen prior to and during host infection. However, since disease-causing microbes constitute only a proportion of the soil microbial population, a high soil microbial activity can lead to competition effects that may ameliorate pathogen activity and survival (Sturz A.V.Carter M.R .and Johnston H.W.(1997).

BIOSTIMULATION AND BIOPEPTICIDES

Bio pesticides can be defined as microrganism-based substances, derived from bacteria, entomopathogenic fungi, plants, nematodes, and viruses, acting against crop pests with different mechanisms of action (Nascimento, T.A *et al*., 2024; Mishra, J *et al*., 2020]. Biopesticides, compared to synthetic pesticides, have advantages such as being environmentally benign and free of harmful residues, not provoking chemical resistance development in pests, having low-cost production, and being easy to use (Rangasamy, K *et al*., 2017). A diverse and balanced soil microbiome acts as a biological barrier, limiting the growth of pathogenic microorganisms and reducing the incidence of crop diseases by competing for nutrients, producing antimicrobial compounds, and inducing plant resistance. Biotic stress in crops is mainly caused by several insects and phytopathogens such as arachnids, bacteria, fungi, nematodes, viruses, and weeds (Qian, X 2020 Venbrux, M 2023; Chandrasekaran, R.; *et al*., 2014).

Crop productivity has been ensured through the application of synthetic pesticides to save crops from pest damage. However, the injudicious use of synthetic pesticides in crop production has resulted in the increased resistance of pests against synthetic pesticides. Moreover, higher pesticide usage affects soil health, wildlife habitats, and water quality and increases health risks for farm workers, farmers, rural populations, and consumers (Chintagunta, A.D *et al*. 2020,; Datta, S *et al*,. 2020; Nawaz, M ***et al*., 2016;** Maciag, T ***et al*., 2023)**. Considering the repercussions of synthetic pesticides, the development of biopesticides derived from microbes and their products can be a viable alternative for plant protection (Swapan, C *et al*.,m 2024; Umesha, S.; *et al*. 2018).

Emerging evidence reveals that biopesticides have been playing a promising role in controlling common insect pests and phytopathogens, and they are also species-specific, eco-friendly, and cost-effective in nature.

Biopesticides coupled with integrated pest management (IPM) can be employed for increasing sustainable agricultural productivity (Mnyone, L.L *et al*., 2010). Microbial species isolated from rhizospheric soil and different ecological niches, such as *Trichoderma viride* , *Metarhizium anisopliae* (Rehner, S.A *et al*., 2017; Sánchez-Rodríguez, A.R *et al*., 2018), *Beauveria bassiana* , nuclear polyhedrosis virus, *Pseudomonas* spp. *Bacillus thuringiensis* , *B. subtilis*, *B. licheniformis*, *B. amyloliquefaciens*, *B. velezensis*, *B. firmus*, and *B. nakamurai* , demonstrated the ability to protect navel seedlings from pests (Ruiu, L,2018)

Therefore, owing to their potential in controlling pests, these microbes could be utilized for the production of different biopesticides. Biopesticides are highly used in horticulture and vegetable cultivation but have a marginal reach in staple food production compared to synthetic pesticides (Marrone, P.G, 2025). Biopesticide market covers nearly 8% of the total plant-protecting products, and around 700 different microbe-based products have been registered globally. Mishra et al. have reported that within the biopesticide market for all crop types, bacterial biopesticides (74%) are predominant in the global market, while fungal biopesticides account for 10%, viral biopesticides constitute 5%, and other biopesticides make up 11%. Generally, the non-microbe-based biopesticides are synthesized through the incorporation of beneficial biological entities and or their derivatives, which protect plants from their predators, For instance, in organic coconut production, *Neoseiulus baraki* coupled with azadirachtin has been used to control the invasive coconut mite *Aceria guerreronis* (Bravo, A.; *et al*., 2011).

Biopesticide applications have gained immense attention in agriculture, and recent updates need to be compiled to emphasize the effective implementation of biopesticides in agriculture (Saddam, B *et al*., 2024; He, Y et al. 2019). Some of the prominent biopesticides playing a significant role in the global biopesticide market and are predominantly from *B. thuringiensis*, *Trichoderma* spp., *B. bassiana*, and *Pseudomonads*. The bacterium *B.*

thuringiensis has been reported for insect control and covers around 2% of the total insecticidal market and around 90% of bacterial biopesticides market (Saddam, B. *et al*., 2024). Its insecticidal properties are also extended to genetically modified products like Bt cotton. Fungi, *Trichoderma harzianum*, and *T. viride*, are the most popular biocontrol representatives in use to oppose various plant pathogens (Mazrou, Y.S et al., 2020). *Trichoderma* spp. developed complex interaction with host plants and rhizospheric microbial communities, performed antibiosis, and induced systemic resistance in plants to oppose crop pests (Mazrou, Y.S *et al*., 2020). Further, *Pseudomonads* are extensively used for biopesticide production due to the secretion of secondary metabolites like 2,4-diacetylphloroglucinol, cyclic lipopeptides, phenazines, pyoluteorin, pyrrolnitrin, and hydrogen cyanide. These compounds show antagonistic potential against pests, which implies biopesticidal activity (Awad, N.E *et al*., 2018).

These microorganisms may play an important role in synthesizing essential compounds like amino acids, enhancing leaf growth rates, or boosting photosynthetic efficiency and stomatal conductance (Eroğlu, G.; 2020; Hou,. Y W. 2021). They also actively participate in nitrogen fixation and enhance plant defenses (del Orozco-Mosqueda 2021). Furthermore, their influence extends to agricultural fields, impacting nutritional and sensory qualities, including flavors and odors (Johnston-Monje,2023).

Regarding plant health under abiotic stress, beneficial microorganisms could play an important role against drought, salinity, extreme temperatures, or low-nutrient regimes (Thamer, S 2011; Prakash, J 2022). These functions are performed by several mechanisms, such as N_2 fixation and mineral solubilization (phosphorus, potassium, zinc), reducing reliance on chemically synthesized fertilizers while directly supplying plants with macro- and micronutrients, as well as plant growth-promoting hormones (Soni, S.K 2022).

On the other hand, beneficial microorganisms have the ability to suppress diverse phytopathogens through several mechanisms. These include the production of antibiotics, lytic enzymes, and siderophores and competing with pathogens for nutrients and space (Marasco, R, 2012). Beneficial microorganisms can disrupt pathogens' quorum sensing (QS) by inhibiting the production of signal molecules through chitinases, pectinases, and lactonases (Saeki, E.K 2020). Some beneficial microbes serve as natural enemies to diverse phytopathogens, exhibit antagonistic behaviors, and compete with pathogenic microorganisms, either inhibiting their growth or outright eliminating them (Saeki, E.K 2020).

Conclusion

microorganisms are fundamental in achieving agricultural sustainability, not just as a support system but as active participants in maintaining and enhancing ecosystem services. their roles in nutrient cycling, pest control, soil health underscore their potential to transform agricultural system into more sustainable, resilient and eco-friendly practises, by harnessing the power of beneficial microorganisms' farmers can improve productivity, reduce environmental impact and ensure the long-term viability of agricultural systems in an increasingly unpredictable world. as research into microbial ecology advances, more ways to incorporate these microscopic entities into sustainable agricultural practices will be driven closer to a more balanced and regenerative to approach to agricultural sustainability. microorganism play an indispensable and multifaceted role in promoting agricultural sustainability, acting as essential drivers of ecosystem health, soil fertility, and crop productivity. the relationship between microorganisms' and sustainable agriculture is one of mutual dependence where microorganism not only enhance the efficiency of natural resources but also ensure long term agricultural viability by maintaining ecological balance in reducing the need for chemical inputs

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