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ENHANCING SOIL HEALTH AND REDUCING LAND POLLUTION THROUGH SUSTAINABLE AGRICULTURAL TECHNIQUES

Chiagoziem Bonfilus Offor[1], Lois Kumiwaa Opoku[2]
[1]Department of Agricultural and Bioresource Engineering,
Enugu State University of Science and Technology, Enugu, Nigeria
[2]Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology, Ghana

**Corresponding Author: Lois Kumiwaa Opoku*

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ABSTRACT---

Healthy soil functions as an active biological system that provides many ecosystem functions, such as maintaining water purity and plant farming strength, and redirecting soil nutrient decomposing processes. The fundamental elements of soil health refer to diverse microorganisms along with their functional activity, sustainable agriculture develops directly from these factors. The capability for a crop production system to generate continuous food output without affecting the environment defines agricultural sustainability. Soil health improves through farming practices and tillage practices since these methods boost the number of soil microorganisms and their diverse compositions as well as their total metabolic functionality. This paper examines external factors that regulate rhizosphere microbiota abundance in addition to evaluating the effects of crop management practices on soil health for maintaining sustainable agricultural productivity.

KEYWORDS: *Soil Health, Soil Micro-Organisms, Farming Practices, Sustainable Agriculture*---------------------

1. INTRODUCTION

Doran & Zeiss present soil health as the operational capacity of vital ecosystems, which enables plant or animal production and maintains both water and air purity alongside preserving the health of plants and animals within limit constraints. Soil health comprises essential (intrinsic) soil system properties that specialists identify using specific health indicators to classify different levels of health. Soil quality describes features that arise from human land use goals, while soil health encompasses inherent characteristics of the living ecosystem that sustains plant and animal productivity alongside water and air purification and biological substance wellness independent of human objectives. Agricultural production needs to significantly rise to meet future food needs since scientists predict a global population will reach 8.9 billion by 2050 (Chapagain et al., 2020). Agricultural production needs to grow two times since new farmland holds scarce availability. Scientists help agricultural sustainability through research-based conversion of soil functionality data into assessment tools, which enable farmers to enhance their land management methods. The main aspects of sustainable farming strategies include interest rate enhancements for soil organic matter content and erosion control through diversification of plants and conservation agriculture (Fageria et al., 2005). The rising need for nutritious food requires sustainable solutions to solve this problem. The approach of sustainable agriculture works to increase agricultural production through climate change management of healthy agroecosystems (Chapagain et al.,2020). Many farming systems faced with degraded land and environmental contamination/Pollution after farmers used excessive chemical fertilizers combined with pesticides for production increases (Lichtfouse et al.,2009). Studies of wheat cultivation within one continuous cycle (monoculture) proved that it led to soil deterioration, which negatively affected groundwater quality while diminishing beneficial microbial groups and making plants more vulnerable to diseases and pests (Doran et al.,2009). Sustainable agriculture provides an integrated ecological approach to handle theoretical and practical food production obstacles by employing natural methods of operation (Timsina, 2018). A framework unifies biological and physical, as well as chemical, alongside ecological principles for creating sustainable agricultural practices (Chapagain et al.,2020). Sustainable agricultural approaches demonstrate potential for fulfilling worldwide food production needs in agriculture (Doran et al., 2002). Root systems establish a rhizosphere, which exists as a narrow soil area near their locations to promote agricultural growth while using minimal or balanced agrochemical input (Devarinti et al.,2016). A complete evaluation of soil health depends on quality indicators that confirm the sustainability of agricultural lands (Singh et al., 2011). Soil biota components represent essential quality indicators according to multiple research studies because these include microbial community composition and population and diversity as well as activity and stability (Lah et al.,2008). Plant residue mineralization transforms organic matter through soil biota which makes available plant absorbable nutrients for growth and development (Berendsen et al.,2012). Microorganisms create enzymes to speed up decomposition processes while also affecting nutrient behavior within the soil (Sahu et al.,2019). The nitrogen transfigurations conducted by bacteria and fungi in soil convert organic material to inorganic forms thereby influencing plant nutrient assimilation and production output and nutritional value (Leaskovar et al.,2016). Basic functions of stable agroecosystems and productive growth exist because of microbial interactions in the soil (Meena et al.,2016). Research shows that the populations of soil microorganisms which include Arbuscular Mycorrhizal Fungi (AMF), active bacteria, and beneficial nematodes and microorganism maintain direct ties with crop yield quantities along with flower quality, soil water storage capacity, and nutrient management functions leading to enhanced plant growth and soil vitality (Dotaniva et al.,2016). Research has confirmed that both organic farming combined with tillage conservation and reduction-based management techniques cause marked increases in soil biota populations in watermelon and globe artichoke crop fields, in clay-loam soil conditions (Vander Heijden et al., 2008). A research study investigated vegetables and field crops (tomato and carrot and rice and French bean) over seven years and demonstrated organic farming methods support higher microbial biomass, carbon in organic agricultural fields as opposed to conventional farming systems (Singh et al., 2015). Soil fungi grew more abundant following conservation tillage implementations compared to traditional tillage measurements over three years of watermelon observation (Lah et al., 2008). The total numbers of earthworms across conventional systems from reduced tillage reached 153 worms/m^2 and using mould board plowing as a form of tillage resulted in 130 worms/m^2. Organic agriculture revealed 45% greater earthworm counts when tiled with mould board plowing at 430 worms per square meter relative to reduced tillage with 297 worms/m^2 (Leskovar et al.,2018).

The improvement of soil health depends on worldwide recognition. Measuring soil health indicators improves the comprehension of sustainability processes in farming practices. The study examines land management activities that affect sustainable agricultural yield production by evaluating rhizosphere microbial activities with their environmental responsiveness.

2. COMPONENT OF SOIL HEALTH IN SUSTAINABLE AGRICULTURE

The scientific community mostly uses "soil quality" with preference to "soil health," which farmers prefer (Kalen et al., 2003). Ritz *et al*., 2019 extensively examined 183 biological indicators for their potential use in soil monitoring. The primary biological indicators included: microbial community structure analysis using terminal restriction fragment length polymorphism techniques; community structure and biomass assessment via phospholipid fatty acid biomarkers; soil respiration and carbon cycling measured through substrate-induced respiration; biochemical activity through multi-enzyme profiling; nematode populations (including maturity index, species diversity, and functional group abundance); microarthropod presence; direct visual observation of soil fauna and flora; invertebrate monitoring using pitfall traps; and total microbial biomass measurements of belowground life. Ritz *et al*. 2019 asserted that more studies need to explore the reaction of biological indicators to various management approaches and their connection to soil functions, together with particular ecological processes. The paper stressed the importance of understanding different soil health components to create successful agricultural monitoring frameworks for national and international use through ground truth data acquisition to build sustainable agriculture systems. Studies confirm that healthy soil delivers five main operational capabilities: it suppresses pathogens while maintaining biological functions and decomposing organic materials and neutralizing toxic substances and cyclically processing water and nutrients (Sahu et al.,2019). Soil quality represents the functional ability of soil to maintain plant and animal productivity and preserve water and air quality and support human health and habitation according to Karlen *et al*. 2003.

Bouma *et al.,*2017 extended the definition of soil quality to "the intrinsic ability of soil to provide ecosystem service despite biomass production." The concept of soil quality serves practical value for assessing ecosystem services according to (Toth et al.,2008). The definition of soil quality now includes biological features together with chemical and physical characteristics (Chaussod et al., 2002). Literature interchangeably uses "soil quality" with "soil health" even though the terms differ in their timescales where "soil health" denotes fast-triggering soil conditions yet "soil quality" encompasses longer-term soil standing similar to human immediate health versus quality of life (More et al.,2010). Soils status gets evaluated with these two measurement terms to determine the agricultural sustainability effects of past present and upcoming land use practices (More et al.,2010).

The improper farming practices which include soil salinization, acidification, compaction, crusting, nutrient depletion and the loss of soil biota diversity and biomass and water imbalance and elemental cycle disruption are responsible for soil degeneration (Lal et al.,2015). Soil biotic organisms perform vital roles in organism suppression and nutrient recycling and water purifying functions (Harris et al.,2009). Soil biotas show fast reactions to whatever modifications occur in soil management practices. Soil biota shows a direct relation to soil fertility and maintains plant health status (Altieri et al.,2003). Research has proven that soil-based organisms play a vital role in boosting land production and soil quality through biological mechanisms for achieving sustainable farming systems (Giller et al., 2005).

2.1 The Role of Microorganisms in Soil Health and Sustainable Agriculture

Soil health is a critical component of sustainable agriculture, and the role of microorganisms in maintaining soil fertility and ecosystem services cannot be overstated. Mycorrhiza, a symbiotic association between plant roots and fungi, is one such example of a beneficial microorganism that plays a crucial role in nutrient cycling and water uptake, ultimately enhancing plant growth and resilience. (Tandon et al., 2019) Soil-borne pathogens, on the other hand, can pose a significant threat to plant health, and understanding their distribution and mechanisms of infection is essential for developing effective management strategies. (Wu et al., 2020)

Cyanobacteria, also known as blue-green algae, are another important group of microorganisms found in soils. These photosynthetic bacteria are capable of fixing atmospheric nitrogen, making it available to plants, and can also improve soil structure through the production of extracellular polysaccharides (Tandon et al., 2019). Nematodes, microscopic worm-like organisms, are ubiquitous in soils and can have both beneficial and detrimental effects on plant growth. Beneficial nematodes may prey on soil-borne pests, while plant-parasitic nematodes can directly damage plant roots and reduce crop yields (Dubilier et al., 2015; Wu et al., 2020).

The diversity and abundance of these microorganisms in the soil are greatly influenced by various soil management practices. For instance, the application of organic fertilizers has been shown to increase the abundance and diversity of soil microbes, improving soil fertility and suppressing the activity of soil-borne pathogens (Wu et al., 2020). Sustainable agricultural practices, such as intercropping and reduced chemical fertilizer application, can also promote the growth of beneficial microorganisms, enhancing the overall soil health and ecosystem services. (Dubilier et al., 2015) (Tandon et al., 2019)

Understanding the distribution and roles of mycorrhiza, soil-borne pathogens, cyanobacteria, and nematodes in the soil ecosystem is crucial for developing sustainable and eco-efficient agricultural practices.

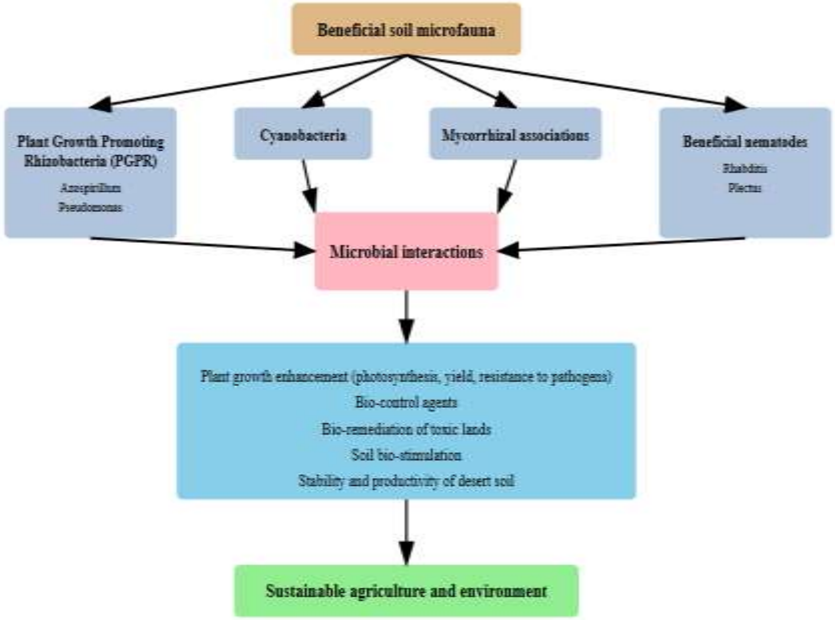

Figure 1; A conceptual framework illustrating the role of beneficial soil microbes and their interactions in fostering sustainable agriculture and environmental stability.

The diagram represents the intricate ties that exist between beneficial microfauna living in soil and sustainable agricultural systems. The upper part of beneficial soil microfauna divides into four main groups: Plant Growth Promoting Rhizobacteria (PGPR), including Azospirillum and Pseudomonas, as well as Cyanobacteria, Mycorrhizal associations, and Beneficial nematodes consisting of Rhabditis and Plectus. These microbial components merge to produce a central interaction space that affects different aspects of soil health by enhancing plant growth (impacting photosynthesis and yield with pathogen resistance) and establishing bio-control agents and tissue remediation systems and through bio-stimulation functions to stabilize desert soil fertility. The sequence of beneficial microorganisms to soil health and finally to sustainable agriculture and environment structure the hierarchical progression toward proper final outcomes.

2.2 Distribution of Microorganisms

Soil is a complex and dynamic ecosystem that supports a vast array of microorganisms, including bacteria, fungi, and archaea (Chen et al., 2019; Dignac et al., 2017). These microorganisms play a crucial role in maintaining the health and biodiversity of the soil (Dignac et al., 2017). Despite our understanding of the importance of soil microorganisms, there is still much to be learned about their distribution and activities within the soil system (Nannipieri, 2020).

It is estimated that a single gram of soil can host up to 1 billion bacteria, representing 1 million species, and up to 1 million fungi comprising up to 10,000 species (Dignac et al., 2017). This immense biological diversity arises in part from the physical and chemical complexity of the soil environment, which includes a diverse soil mineral matrix. Different soil mineral assemblages have been found to favor the development of specific microbial communities through their surface characteristics, nutrient content, and stage of weathering. (Finley et al., 2021). Moreover, plant diversity has been shown to have a positive effect on microbial biomass and respiration across global terrestrial ecosystems, highlighting the importance of plant diversity in maintaining belowground ecosystem functioning. (Chen et al., 2019)

The activities of soil microorganisms are vital to the ecosystem services provided by soils, such as nutrient recycling, carbon sequestration, and the regulation of greenhouse gas emissions. Despite this, the volume occupied by microorganisms in the soil is less than 1% of the available soil volume, as most micro-niches are considered hostile environments. (Nannipieri, 2020) The complex interactions between microbes, plants, and animals are often mediated by molecular signals, and the use of advanced techniques like meta transcriptomics and soil proteomics is still a technical challenge, leaving many of these activities poorly understood.

While significant progress has been made in understanding the distribution and importance of soil microorganisms, there are still many unanswered questions that warrant further investigation.

2.3 Beneficial Microorganisms for Soil Remediation

Soil remediation, the process of restoring contaminated or degraded soil to a healthier state, has emerged as a crucial environmental concern in recent decades. While traditional approaches such as physical and chemical treatments have been employed, the use of beneficial microorganisms has gained significant attention due to its eco-friendly and cost-effective nature (Ethica et al., 2020) (Liu et al., 2023).

Microbes are indispensable components of soil, playing a crucial role in reinforcing soil fertility, structural organization, and biogeochemical cycling (Tandon et al., 2019). The potential of microbial diversity has been exploited to develop strategies and technologies to improve soil properties. Numerous studies have demonstrated the remarkable capabilities of microorganisms to degrade, transform, or immobilize a wide range of pollutants in contaminated soils, making them a promising solution for addressing this pressing environmental challenge. (Ethica et al, 2020; Tahri et al., 2021; Bell et al., 2016; Liu et al., 2023). Bioremediation, the utilization of microorganisms to break down or transform harmful substances, has become a widely accepted and extensively studied method for soil remediation (Bell et al, 2016; Liu et al., 2023).

Groundwater contamination, often resulting from agricultural activities, has further heightened the need for effective soil remediation strategies. Bioremediation, as an environmentally friendly, socially acceptable, and economically viable approach, has emerged as one of the most promising solutions to this issue (Ethica et al., 2020). The use of microorganisms, including fungi, algae, bacteria, and yeast, with beneficial biological activities, has been a central focus of bioremediation efforts.

2.3.1 Sustainability and Biodiversity of Soil

Soil biodiversity encompasses all living organisms within the soil. The Convention on Biological Diversity specifies soil diversity as "the variation in soil life from genes up to communities and the entire ecological network from micro-habitats to landscapes" (Kalen et al.,2003).

The combination of expanding human numbers with climate-caused environmental deterioration and degraded soil quality alongside shrinking farmland has put severe pressure on worldwide sustainability resources (Ritz *et al*., 2019). Soil microorganisms link roots to soil while performing nutrient cycling functions and decomposing organic materials and sensitively detecting ecosystem changes to report specific soil operational conditions (Sahu et al.,2019).

The interconnected activities between microbe populations alongside their pattern of interactions with plants and soils generate a long-lasting ecological balance in the ground, which enables plant development while boosting crop productivity. The essential nature of understanding microbial community operations requires knowledge about their functions and communications in plant-soil systems for preventing the damaging practice implementation.

The vital function of soil microorganisms establishes a root interface with the soil while they perform nutrient cycling together with organic matter decomposition and quick adaptation to environmental change. Soils depend on these indicators as their main functional status that secure ecological balance. The complex relation between microbial communities and soil and plants generates a sustainable soil environment that supports crop growth as well as development and ensures continued productivity. Study of microbial operations in plants and soil remains essential to stop destructive farming procedures, which might permanently damage the entire ecosystem. The study of microbial behavior delivers dependable information about soil conditions along with farming sustainability metrics.

The planet's largest pool of biodiversity exists within the realm of soil biota. Soil biodiversity, which extends across the globe, lets functions operate to sustain ecological systems. Several essential functions result from soil habitation, including shelter for land and water-dwelling life forms and climatic stabilizers and pollutant controllers, as well as water quality protectors and food providers. The stability of ecosystems depends on soil biota, which controls vital environmental processes that underline its worldwide importance in sustainability-based initiatives.

The map below shows the United States' biodiversity across regions. Based on the map legend, the "Soil Biodiversity Index" ranges from "High" (green) to "Low" (orange), with the US generally showing a mix of moderate to high biodiversity in the East and more variable, often lower biodiversity in the West and Central regions.
The highest soil biodiversity in the US appears to be in regions with:
-More consistent rainfall, Temperate climates, Mixed forests and diverse vegetation, Less intensive land use.

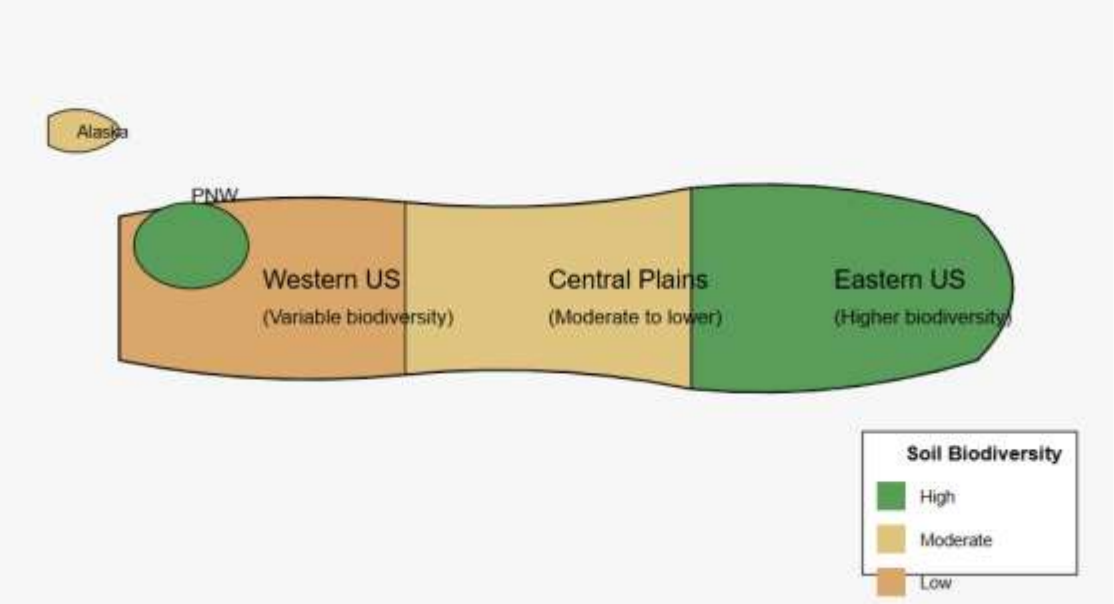

Figure 2; The United States soil biodiversity across its regions.

3. FARMING PRACTICES TO IMPROVE SOIL HEALTH COMPONENT

Soil health is a crucial component in ensuring global food security and environmental sustainability. Conventional agricultural production systems have often been characterized by intensive chemical and tillage-based practices, leading to the degradation of soil health and ecosystem functions. (Arriaga et al., 2017) However, emerging research has highlighted the potential of more sustainable farming approaches to enhance soil health and productivity. Soil health is a crucial component in ensuring global food security and environmental sustainability. Conventional agricultural production systems have often been characterized by intensive chemical and tillage-based practices, leading to the degradation of soil health and ecosystem functions. (Arriaga et al., 2017) However, emerging research has highlighted the potential of more sustainable farming approaches to enhance soil health and productivity. The integration of beneficial microorganisms, such as plant-growth-promoting fungi and bacteria, has been identified as a promising approach to enhancing soil health and productivity (Banerjee & Mandal, 2020). These microorganisms can play a vital role in remediating degraded soils, improving nutrient cycling, and supporting plant growth. (Banerjee & Mandal, 2020) Furthermore, the adoption of conservation agriculture techniques, including reduced tillage, cover cropping, and crop rotation, can help maintain soil structure, increase organic matter, and promote the activity of soil biota. (Arriaga et al., 2017)

3.1 Crop Rotation

Crop rotation, a fundamental practice in sustainable agriculture, can enhance soil health by promoting microbial diversity and nutrient cycling. The introduction of diverse crop species through rotation can stimulate the growth and activity of a broader range of soil microorganisms, leading to improved nutrient availability, enhanced soil aggregation, and overall improvements in soil health.(Pagano et al., 2017) Intercropping different plant species has also been shown to be beneficial, as it can increase carbon fixation by plants, transferring carbon to the soil, especially via mycorrhizal associations, thus modifying interplant interactions and promoting a more diverse and resilient soil ecosystem. (Pagano et al., 2017)

3.2 Cover Cropping

The utilization of cover crops, such as legumes and grasses, can significantly contribute to the enhancement of soil health. Cover crops help maintain soil cover, increase organic matter input, and promote the activity of soil biota, including beneficial microorganisms. (Fageria et al., 2005) The incorporation of diverse cover crop mixtures can further diversify the soil microbiome, leading to improved nutrient cycling, soil structure, and overall soil health. (Chapagain et al., 2020)

Moreover, the strategic use of biocontrol agents, biofertilizers, and the management of exposure to pesticides can significantly impact the soil microbial community and its ecosystem functions. (Pagano et al., 2017)

3.3 Reduced Tillage

Conventional tillage practices can disrupt the delicate balance of soil microorganisms and lead to the erosion of soil structure. In contrast, reduced tillage or no-till farming can help maintain soil aggregation, increase organic matter content, and promote the abundance, diversity, and activity of soil microbial communities (Kim et al., 2020) (Crowley et al., 2018).

3.4 Organic Matter Management

The incorporation of organic matter, such as plant residues, compost, and animal manure, is a crucial component of sustainable farming practices. Organic matter serves as a food source and habitat for a diverse array of soil microorganisms, stimulating their growth, activity, and diversity. (Oldfield et al., 2017)

4.0 Impacts on Soil Health

The adoption of these sustainable farming practices can lead to significant improvements in various aspects of soil health, including physical, chemical, and biological properties. For instance, reduced tillage and the incorporation of organic matter can enhance soil structure, increasing the soil's ability to absorb and retain water, thereby improving its water-holding capacity. Additionally, the presence of diverse cover crops and crop rotations can enrich the soil's nutrient status, promoting a more balanced and readily available nutrient supply for plant growth. (Arriaga et al., 2017) Furthermore, the stimulation of soil microbiome diversity and activity through these practices can enhance the soil's ability to regulate nutrient cycling, control pests and pathogens, and mitigate the effects of environmental stresses, such as drought and flooding (Pagano et al., 2017; Girvan et al., 2003; Arriaga et al., 2017; Crowley et al., 2018).

4.1 Soil Structure Improvement

The adoption of sustainable farming practices, such as reduced tillage and organic matter management, can significantly enhance soil structure. Increased soil aggregation and improved porosity contribute to enhanced water infiltration and water-holding capacity, ultimately supporting plant growth and resilience (Lal, 2020). Improved soil structure also promotes the abundance, diversity, and activity of soil biota, creating a more favorable habitat for beneficial microorganisms (Khan et al., 2024).

4.2 Nutrient Cycling Enhancement

Sustainable farming practices, including cover cropping, crop rotation, and organic matter addition, can promote the activity and diversity of soil microorganisms. These microorganisms play a crucial role in transforming, mobilizing, and making available essential nutrients for plant uptake, reducing the need for synthetic fertilizers, and enhancing the overall nutrient status of the soil (Bulygin et al., 2020).

4.3 Microbial Activity Stimulation

The integration of diverse farming practices, such as cover cropping, reduced tillage, and organic matter management, can significantly stimulate the activity and diversity of soil microorganisms. These microorganisms contribute to the regulation of various ecosystem functions, including nutrient cycling, organic matter decomposition, and the suppression of soil-borne pathogens, ultimately enhancing the overall health and resilience of the soil (Girvan et al., 2003) (Pagano et al., 2017)

5.0 CONCLUSION

The adoption of sustainable farming practices, such as cover crop utilization, crop rotation, reduced tillage, and organic matter management, can significantly contribute to the enhancement of soil health. These practices promote the activity and diversity of beneficial soil microorganisms, leading to improvements in soil structure, nutrient cycling, and overall soil resilience. This review discussed how soil health affects intensive crop farming systems alongside methods for gauging sustainable agricultural systems' soil health elements. Soil health evaluates the biological properties through measures of microorganism numbers along with diversity patterns and active levels together with stable biocenosis dynamics. Soil microorganisms combined with rhizosphere microorganisms exert influence on plant composition and also determine both productivity levels and sustainability performance. Different types of destructively and constructively affecting nematodes reside within the soil profile. Firstly, microbial populations along with soil nutrient levels rise in organic systems while physical qualities and microbial diversity both grow stronger. The evaluation of soil health indicators needs better measurement methods to expand our comprehension about how production approaches and environmental variables affect the physical, biological, chemical functioning and evolution of soil-rhizosphere-plant systems toward short- or long-term sustainability.

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