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Review

Significance of Soil Health Management in Sustainable Agricultural Systems

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Abstract
Soil health plays a vital role in sustainable agriculture to ensure food security and preserve the environment. The global food demand is increasing daily, and crop plants face many challenges due to the degeneration of soil as well as water and air pollution as a result of the nonjudicious application of chemicals. Collaborative efforts by farmers, policymakers and researchers to promote sustainable practices are currently needed. Strategies such as cover cropping, crop rotation, reduced tillage, organic matter addition, and integrated nutrient and pest management are required for improving soil health and ensuring long-term agricultural viability. Management options for improving soil health are also necessary to mitigate different biotic and abiotic stresses and enhance crop yield. This chapter noted important variables to consider when evaluating the soil biodiversity, soil quality and principles as well as components of soil health in sustainable agril systems.

Keywords: soil biodiversity, soil health, sustainability

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1 INTRODUCTION

The ability of soil to work within the limitations of ecosystems and land uses as a vital living system to support the yield obtained from plants and animals, conserve and enhance the quality of water and air and improve the health of vegetation and creatures is known as soil health[1]. Soil health includes several elements, such as soil texture, nutrient content, organic matter, pH and microbial diversity. Soil health management needs to be the top priority for all parties involved in agricultural development to maintain agricultural production and environmental quality[2]. Biological components are essential to the operation of ecosystems within land use limits because they are able to support soil biological productivity while also preserving the standards of the surrounding environment, and they eventually improve the health of humans, animals and plants[3]. The primary important markers of soil health are the percentage of organic matter in the soil and the status of the microbial population in the soil[4]. On the other hand, soil degeneration is the process that diminishes the soil's capacity to dispense products or services today or in the coming days[5]. The primary causes of degraded soil include the overuse of chemical fertilizers, improper nutrient management and soil pollution[6]. Among the factors hampering the sustenance of agril systems, the use of chemical agro-inputs is a major factor that leads to the degradation of soil fertility. The use of innovative scientific agronomic approaches can help to sustainably manage the world's soil resources, which is a major step in finding answers to these problems[7]. In the 19th and early 20th

centuries, when the world's population was only 38% of the current population, the objective of soil management was to sustain agronomic production to feed them[7]. To maintain agriculture and the planet for upcoming generations, immediate action is necessary to create production systems that fulfill our food, fiber and energy requirements by relying minimally on exhaustible petrochemical stocks and maximally on eternal supplies[8]. Crop plants are facing continuous competition and challenges because of various stresses. Plants can withstand unfavorable conditions caused by sudden changes in environmental features by initiating their intrinsic mechanisms[9]. Soil microorganisms have been found to strongly support plants in mitigating many stress conditions[10,11]. These microbes catalyze the amelioration of stress by participating in the cycling of nutrients, maintaining the fertility of soils and disease resistance of plants, thus sustaining crop production[12,13]. Biomulching adds organic matter to the soil and enhances the density of soil microbes, which then increases the organic carbon content of the soil[14]. Optimum crop growth is supported by healthy soil because it offers vital nutrients, water and a stable physical environment, which leads to agricultural sustainability. This chapter provides detailed information about soil health management and its impact on agricultural systems.

2 SOIL BIODIVERSITY AND ITS SUSTAINABILITY

The term "soil biodiversity" describes all living things found in the soil. The variation in life below the soil surface, from genes to communities developed *vis-à-vis* the ecological complexes to which they belong and involve, from microhabitats to landscapes of soil, is defined as soil biodiversity[15]. Some factors, such as an increase in the world's population, a change in the global climate, the degradation of soil and the disappearance of arable land, create a situation for increased use of natural resources and maintain global sustainability[16]. Soil microbes act as important indicators of specific functions in soil ecosystems. They link soil with plant roots, are involved in nutrient recycling and decomposition of organic matter and respond quickly when any change occurs in agroecosystems[17]. The growth, phenological changes and yield of a crop can be supported by a sustainable soil environment that is established by the functions of the microbial community and its relationship to the soil and plants. Therefore, to prevent poor management options before irreversible damage occurs in the soil ecosystem, it is necessary to understand the purpose and behavior of microbial communities in soil and their communication methodology with plants. In fact, the sustainable health of soil and crop production can be diagnosed by using comprehensive knowledge of microbial activities[18]. Soil functions and biodiversity encompass many important elements, such as water quality, food production, climate, pollution remediation and habitat for above- and underwater biota. They are vital to the advancement of global sustainability[19,20]. One of the world's greatest repositories of biodiversity is the soil biota. It influences ecosystem stability by controlling species asynchrony, aboveground net primary production, and plant diversity[21]. Soil biota, associated with plant roots, support ecosystem stability through their influence on the response of plant species to environmental changes, such as increased plant adaptability to harsh pressures (drought, salt, and temperature) because of climate change[21].

Soil biodiversity worldwide may be in danger, particularly in places with dense populations and intense land use[22]. Intensive grazing, decreasing soil organic matter content, environmental pollution, soil erosion and degradation, excessive human use of natural sources, climate change, etc., are some stressors that cause a loss of soil biodiversity[23]. Therefore, assessing the threats to soil health and taking appropriate action are essential for ensuring the sustainability of agriculture worldwide. The maintenance of crop growth and productivity requires an understanding of how soil biota mediate soil processes. The collective characteristics and functions of soil include microbial population control, nutrient cycling and decomposition[24]. The cycling of nutrients, particularly nitrogen, and decomposition of organic residues are the ecological processes that occur in soil[19,25]. Soil biota typically drive both processes[24]. Species richness is not strongly correlated with nitrogen cycling potential, as is species biodiversity in soil. Decreased biodiversity among soil decomposers leads to slower rates of litter decomposition in all biomes, which in turn reduces nitrogen cycling[25]. A crucial agronomic technique to encourage soil biota-regulated decomposition and transformation is appropriate for organic residues, given their innate vulnerability to both enzymatic hydrolysis and physical breakdown[26]. Microbial capacities are generally linked to soil health and agricultural sustainability through their functional abilities for organic matter decomposition, minimum degradation and remediation of soil, nutrient accumulation, mobilization, fixation, and recycling[18].

3 SOIL QUALITY FOR SUSTAINABLE MANAGEMENT OF SOIL

The development of systems for sustainable field management is a complex process that involves important factors such as the usefulness of systems to humans, their efficiency in using resources and their capacity to preserve a beneficial environment for most plant species as well as humans[19]. The creation of agricultural management systems for maintaining a balance between the demand for unaltered environments and sufficient food and fiber production is one of our greatest challenges. Tom Franzen, an American grower from the Midwest, stated that sustainable agriculture also sustains people and conserves the soil[20]. Similarly, Acton and Parr et al. reported that the quality of soil is the primary conduit between conservation agricultural practices and the fulfillment of the basic objectives of sustainable agriculture[21]. In summary, the main indicator of sustainable field management is the evaluation of the health of the soil and the degree of change after a period of time[22]. In several places on Earth, techniques for thorough management of fields and imbalances in N, C, and the water cycle in soils involve measuring the quality of surface and subsurface water in danger.

In the United States, agriculture is the primary cause of nonpoint-source water pollution[23]. In Europe and North America, the nitrate form of nitrogen is the most serious contaminant of water, which is primarily caused by animal manures, atmospheric deposition, intensive agriculture on inconvenient land and commercial fertilizers. Over the past 30 years, the nitrogen input rate to terrestrial ecosystems has doubled due to changes in the nitrogen cycle caused by humans. This is the reason for the significant increase in the quantity of nitrogen transferred from land to the air as well as to streams, estuaries and coastal oceans[24]. The quality of water is improved by management techniques such as tillage, crop growth schedules, and the use of fertilizers and pesticides. Furthermore, altering the ability of land to generate and absorb significant atmospheric gases, such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), can change the quality of the atmosphere. A deeper understanding of the impact of soil management on soil processes is urgently needed to reduce global climate change and ozone depletion caused by increased concentrations of greenhouse gases and modified cycles of hydrology[25]. In conclusion, agricultural sustainability[26,27], environmental quality[28] and consequently the health of vegetation, other creatures and humans[29,30] are influenced by the health and quality of soil. By converting the knowledge of science and data on soil function into useful implements and techniques that help soil managers evaluate the sustenance of those management options, scientists have significantly contributed to sustainable land management[31,32]. Soil assessment regarding health and quality is specifically required to identify the problematic lands used for production, determine the actual estimates of crop production, track the variations in environmental quality and sustainability, as they are related to agricultural management, and support government agencies in developing and accessing sustainable land use and agricultural policies[33]. Soil managers and policy makers cannot effectively or meaningfully use a single approach to evaluate or index soil quality due to its complexity[34]. However, the most effective way to connect research and practice in the evaluation of sustainable management practices probably involves the application of straightforward soil health and quality indicators that growers and other soil managers can understand easily[35,36].

4 PRINCIPLES AND COMPONENTS FOR SUSTAINABLE SOIL HEALTH

The terms "soil health" and "soil quality" are often considered similar in the scientific literature, and some people even suggest that these terms have the same functional meaning. On the one hand, farmers prefer "soil health", but scientists prefer "soil quality" on the other hand[37-40]. The five principles for obtaining good soil health are increasing plant biodiversity, maintaining continuous living roots in soil, minimizing soil disturbance, maintaining soil cover by maintaining stubbles and adding livestock. To monitor soils, 183 biological indicators have been identified[24]. The readily available biological indicator organisms are soil microbial group and community structure following methods involving terminal restriction fragment length polymorphism[1]; soil microbial community structure and biomass use extracted lipids, specifically phospholipid fatty acids (PLFAs), as signature lipid biomarkers[14]; respiration of soil and carbon (C) cycling from a number of substrate-induced respiration[20]; biochemical procedures from multienzyme profiling[41]; nematodes, involving maturity indices (the distribution of nematodes across functional groups), group marking and abundance of individual functional groups[42]; microarthropods[43]; on-site visual recording of soil fauna and flora[7]; pitfall traps for ground dwellers and soil invertebrates[44]; and biomass of microorganisms[18], the overall quantity of underground life. However, more research is necessary to determine how these biological indicators respond to changes in management practices, how they are connected to soil functions, and how they are utilized to clarify particular ecosystem processes.

In general, determining the components of soil health (Figure 1) is critical to the sustainable development of our agricultural systems as well as the effective utilization of national and international monitoring systems (ground truth data) for agriculture. Soil quality is decreased by improper agricultural processes such as salt deposition, acid deposition, soil compaction, crustation, a lack of nutrients, a decrease in the biomass of soil biota and biodiversity, water disparity and disturbance of nutrient cycling[34]. Soil biota typically react quickly to soil management techniques and are linked to the squelching of microorganisms, cycling of nutrients and detoxification of stored water[1,34]. Plant health, soil fertility and soil biota are closely correlated[45]. One of the most important approaches to achieve agricultural sustainability is the role that soil biota play in enhancing soil fertility and the yield obtained from land through biological processes[46]. To provide microorganisms with a physical habitat, soil aggregates are important for determining the overall population of microorganisms[47]. The quantity of bacteria, fungi and actinomycetes found in the soil aggregates ranged from 1-3mm in humic rendzina (heavy loam calcareous) soil, which was greater than that of aggregates ranging from 5-7mm[47]. Furthermore, the population of soil microorganisms can be affected by soil pH, total organic C, vegetation on land and climate[48]. According to an evaluation of the impacts of environmental and management factors on rhizosphere microbial density and biodiversity, soil type was found to be a significant variable influencing the microbial population[49].

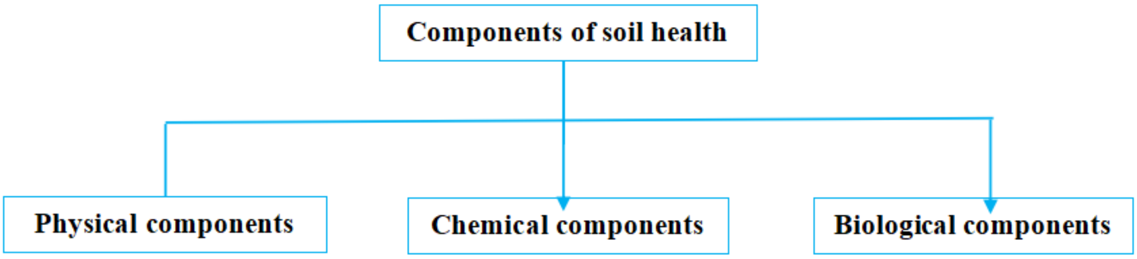

Figure 1. Components for Soil Health Management.

The three zones that make up the rhizosphere and envelope the plant root zone are the rhizoplane (root surface), the root and the soil itself, which are considered to be home to endophytic microbes[50]. As a complex hotspot for microorganisms, the rhizosphere is home to viruses, bacteria, fungi, nematodes, algae, protozoa, archaea and arthropods[51]. Microorganism diversity increases near the rhizoplane but decreases with increasing distance from the rhizoplane. The C concentration, which directly correlates with the distance from the rhizoplane, provides an explanation for this fact[52]. Furthermore, the rhizosphere effect, which refers to the release of organic matter and root exudates, is necessary for the active development of the microbiome[53]. The intricate relationships within the rhizosphere demonstrated that every element, soil, root and microbe could be controlled or designed to support the growth of plants and plant development[54]. For instance, a deeper understanding of the interactions and connections between rhizosphere root and soil microbes can minimize our reliance on chemical fertilizers by employing advantageous microorganisms[55].

The development of zone specific, regional or agroclimatic microbial inoculants holds promise for successful agricultural and environmental applications, as evidenced by studies on habitat-specific functional microbial taxa as important indicators[18]. Farmers now have the opportunity to decrease synthetic farm inputs (chemical fertilizers and pesticides) along with the increase in the use of integrated nutrient management and pest control options for the sustenance of agriculture because of the production and effectiveness of commercial microbial inoculants such as biofertilizers and microbe-based decomposers[18].

Nonetheless, it is crucial to determine the costs and benefits of introducing exogenous good bacteria into agricultural fields and to explore ways to reduce fertilizer inputs. In fact, it has been hypothesized that below-ground biodiversity and plant productivity under various environmental conditions are related[56]. By utilizing a variety of strategies, including enhanced yield, nutrient use efficiency by plants and specific uptake of Fe and P[57,58], rhizosphere microbes can foster plant growth and defend against invasion by pathogens. Additionally, they can serve as a first line of defense for plant roots against soil-borne pathogens[59]through antibiosis[60], inducing systemic resistance[61] and parasitism on soil farms[62]. According to the most extensive research, the organisms found for their beneficial impact on crop plants in the rhizosphere are known as beneficial rhizosphere microbes, which include bacteria for nitrogen fixation, plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), mycoparasitic fungi, biocontrol microbes and protozoa. Every group is essential to the health of plants[63]. However, depending on the plant and its surroundings, their interaction with plants may be beneficial or detrimental[64]. Beneficial microorganisms may enhance plant nutrition and both directly and indirectly promote plant growth[67]. Rhizobacteria, which promote plant growth, are a diverse group of bacteria. Bacillus, Pseudomonas, Rhizobium, Azospirillum, Serratia, Stenotrophomonas and Streptomyces are the most often utilized PGPR[67]. AMF improve plant nutrient availability and water use efficiency because they can thrive in a variety of unpleasant environments. Cyanobacteria provide a reliable nonstop biomass supply of soluble organic matter called secondary metabolites, which improve crop yield and act as growth promoters. Many kinds of nematodes, both beneficial and toxic, can be found in the soil profile. Beneficial nematodes increase plant output, while harmful nematodes decrease it[66].

5 CONCLUSION

The soil biota, a factor of soil health, includes microbial variation, activity, abundance and community stability. The variability and quantity of microorganisms found in the soil and rhizosphere influence the productivity, sustainability and composition of plants. To maximize crop yield, protect the environment and guarantee food security in a changing world, healthy soil is crucial. Farmers, legislators and researchers must collaborate to advance and implement sustainable farming methods to accomplish these goals.

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Conflicts of Interest

The author declared no conflict of interest.

Data Availability

Data sharing is not applicable to this review as no datasets were generated or analyzed during the current study.

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Author Contribution

Mondal T conceptualized the study, developed the research framework, and drafted the primary manuscript. Mondal D conducted the data analysis, interpreted the results, and critically revised the manuscript for intellectual content. Mishra A performed the literature review, contributed to methodological development, and assisted in drafting sections on soil health management practices. Saha A carried out the statistical analysis, prepared the figures, and reviewed the manuscript for technical accuracy. Mishra AK supervised the research process, provided key resources and materials, and conducted the final review of the manuscript to ensure its readiness for publication.

Abbreviation List

AMF, Arbuscular Mycorrhizal Fungi
PGPR, Plant Growth-Promoting Rhizobacteria
PLFA, Phospholipid Fatty Acid

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