



Soil Health Management and Sustainable Crop Production: A Comprehensive Review

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ABSTRACT

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Soil health is the cornerstone of sustainable crop production and long-term food security. Soil is a dynamic and living system that performs vital physical, chemical, and biological functions, such as nutrient cycling, water retention, carbon storage, and plant growth regulation. However, over-cultivation, erosion, nutrient imbalances, and climate variability have accelerated soil degradation in many agricultural regions. This review presents an integrated analysis of the key components of soil health and their direct impact on crop productivity. These include physical properties such as soil structure, porosity, and density; chemical parameters such as nutrient availability and pH balance; and biological indicators such as microbial diversity and enzyme activity. Additionally, management strategies that enhance soil resilience such as organic amendments, conservation tillage, crop rotations, integrated nutrient management, the use of biofertilizers, and efficient irrigation have been evaluated. Agroecologically based practices and accurate monitoring systems have also been identified as important for improving soil function while minimizing environmental impacts. Strengthening soil health not only ensures production sustainability but also promotes ecosystem services, climate adaptation, and resource efficiency. Therefore, integrated soil management based on scientific assessment, policy support, and farmer participation is essential.

Keywords: Soil health, Sustainable agriculture, Nutrient management, Conservation practices, Crop productivity.



1. Introduction

Soil is a complex, dynamic, living system that is essential for the biological productivity of terrestrial ecosystems. It is a major resource for food, fuel, fiber, and raw materials production for humankind. In addition, soil health indirectly supports human life on the planet through the maintenance of air quality, water quality, climate regulation, carbon

balance, and organism health (Jaster, 2010). Degradation of soil affects its capacity to perform these functions, ultimately endangering the sustainability of agricultural production systems and compromising the reliable supply of vital ecosystem services (Basch et al., 2017). Despite the multiple functions provided by soil for humanity, land-use change and degradation have deteriorated soil conditions worldwide, with significant adverse impacts on the plant-soil-water-nutrient and plant-pest-pathogen interactions. The Global Land Outlook Report indicates that every year, over 24 billion tonnes of fertile soil are lost through erosion, with a staggering 6.5 million hectares of arable land and 32 million hectares of productive drylands degraded. In parallel with rising global population and increasing food consumption, crop productivity must be maintained without compromising soil health and the provision of soil-driven ecosystem services. Enhanced soil health interventions, soil health principles, and sustainable crop production practices need to be implemented to ensure much-needed resilience to climate change and emerging environmental pressures such as the increasing frequency of flooding and drought.

2. Conceptual Framework of Soil Health

Soil health has become a global focus among scientists, policy makers, practitioners, and the public in pursuit of sustainable crop production systems (Doran & Zeiss, 2000). The concept of soil health reflects the condition of soil as a living ecosystem, defined as the continued capacity of soil to function as a vital living ecosystem. Soil health encompasses multiple dimensions, the most important of which are physical, chemical, and biological health. Soil physical health focuses on aspects such as aeration, bulk density, compaction, drainage, porosity, temperature, texture, and water-holding capacity, all of which influence crop production. Soil chemical health emphasizes the supply of nutrients to growing crops, with soil fertility being a major aspect of agricultural production. Soil biological health reflects the presence and activity of soil organisms and microorganisms, including bacteria, fungi, and earthworms; soil enzymes and organic carbon reservoirs act as further indicators.

Soil plays a fundamental role in the terrestrial environment by acts as a conduit for rainfall, a reservoir for plant nutrients, and as a medium for root anchorage; its storage, detoxification, filtration, and mineralization functions have a significant impact on pollutant transport. Many soil types currently under intense cultivation show the signs of degradation. When these soils become unfit for cropping, farmers often expand their cultivated areas to less degraded soils, further accelerating soil degradation. Therefore, adopting a holistic approach to soil health is critical to achieving a sustainable agricultural system that can meet the food demands of an ever-growing population.

3. Soil Physical Health and Its Implications for Crop Production

Soil plays a complex role in the functioning of cropping systems because its properties provide natural benefits, potential hazards, and trade-offs between management objectives (Doran, 2002). It offers a plant growth medium, supplies nutrients and water, and

controls pest and pathogen populations. In contrast, soil can also act as a negative influence, and the nature of these influences changes with the intensity and frequency of tillage practices. Therefore, assessing soil physical health requires an understanding of soil functions, processes, and the natural and anthropogenic factors that affect these factors over time. Soil health refers to the capacity of soil to function as a vital living system to sustain biological productivity, promote air and water quality, and maintain the health of plants, animals, and humans (Jaster, 2010). It is a dynamic condition that can change from year to year because of natural variability and anthropogenic activities and is often used interchangeably with the term “soil quality”. Soil quality and soil health are important because they significantly influence not only agricultural productivity but also ecosystem functioning. Soil health criteria include physical, chemical, and biological indicators that are relevant to soil health. The following sections summarize how indicators of soil health can be assessed for soil physical characteristics, soil chemical properties and nutrient availability, and soil biological health.

4. Soil Chemical Health

Soil health directly influences nutrient availability for crops. Nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium availability is often assessed through soil chemical tests. A soil with adequate chemical nutrients is ready for crop production, though the testing results may require expert interpretation. Soil nutrient management indices for sustainable crop production, such as the Food and Agriculture Organization soil fertility index and others, are also available (Doran, 2002). Soil nutrient indices speed up nutrient recommendation processes based on soil fertility tests, further enhancing crop yields without degrading soil quality.

Soil pH determines nutrient solubility and the chemical form of nitrogen, phosphorus, sulfur, iron, and other nutrients. Low soil pH renders elements like aluminum, cadmium, copper, iron, lead, magnesium, manganese, nickel, and zinc more soluble. Reducing soil acidity through lime or certain organic amendments increases nutrient availability and improves the growth of crops sensitive to high acidity.

5. Soil Biological Health

Microbial communities, enzyme activity, and soil biota play crucial roles in soil biological health and affect crop production and resilience. Soil microbes contribute to soil structure, pathogen suppression, plant nutrient availability, and organic matter decomposition (Singh et al., 2023). They produce polymers and biocrusts that influence macroporosity, pore-size distribution, hydraulic conductivity, and aggregate stability, mitigating the effects of compaction. Microbial enzymes facilitate nutrient mineralization, organic matter turnover, and pollutant degradation, providing insights into nutrient transformation and biogeochemical cycles. A 50-year study on wheat systems found that less-disturbed soils hosted more diverse bacterial communities and greater relative abundances of oligotrophic taxa adaptable to stress. Systems featuring no-tillage, cover crops, and unmanaged grasslands enhanced soil organic carbon, total nitrogen, and nutrient availability. Soil health indicators, including

carbon mineralization potential and enzyme activities, were higher under conservation practices. Consequently, soil diversity indices improved, oligotrophic-bacteria abundance rose, and microbial-evenness levels increased, fostering greater resilience to stress. Understanding microbial-adaptation strategies under different management practices informs sustainable agriculture.

6. Management Practices for Soil Health Enhancement

Soil health can be enhanced through a variety of management practices that sustain or improve its beneficial attributes. These practices include the application of organic amendments, the management of tillage and crop residues, the diversification of crop rotation, the maintenance of balanced nutrient supply, the use of biological inoculants, and the regulation of irrigation water. Conservation agriculture involves multiple practices that help sustain soil health and yield.

Soil organic matter content is the critical property that influences soil health and is affected by management practices. The application of organic amendments helps increase soil organic matter. Organic amendments such as animal manure, green manure, and crop residues enhance soil organic matter and a range of soil attributes. The supply of 10 to 90 kg of N ha⁻¹ year⁻¹ through animal manure and crop residues has raised soil organic carbon content (Sainju et al., 2003).

Conservation tillage minimizes soil disturbance and retains crop residues on the surface, improving soil properties. Conservation tillage difference demonstrated an increase in soil organic carbon, N, C:N ratio, and CEC (Cation Exchange Capacity) without affecting crop yield under a range of cropping systems (Basch, 2017).

Continuous monoculture encourages soil degradation. Formation of healthy and viable cropping systems through diversification maintains soil quality and crop productivity. Introducing pulses and legumes into cereal cropping systems sustains crop production and soil health. Rotation of wheat with mustard and lentil helps maintain wheat yield in till vs. zero-till cropping systems. Rotation of wheat with chickpea improves soil quality and water retention in the semi-arid region (Walia et al., 2024).

Soil degradation occurs due to depletion of essential plant nutrients. Biofertilizers help supplement the nutrient requirement of crops. An increase in soil macro- and micronutrient availability is observed after the application of biofertilizers under rice–wheat and cotton–wheat cropping systems. Application of balanced fertilization along with integrated nutrient management under rice–wheat cropping systems sustains soil health.

Global climate change and efficient irrigation use have become critical issues. Alternate wetting and drying improve water use efficiency and soil properties. A combination of soil moisture evaporation meter and satellite sensors at multiple crop growth stages helps in irrigation scheduling to sustain soil health.

6.1. Organic Amendments and Soil Organic Matter Accumulation

Organic amendments, such as farmyard manure, wheat straw, and green manure, enhance soil health and are essential for sustainable agriculture in the Indo-Gangetic Plains (Lucas, 2013). The application of organic manures supplemented with nitrogen improves soil organic matter (Walia et al., 2024). Organic amendments mitigate soil degradation, including erosion, organic matter loss, and reduced biodiversity caused by intensive agriculture. Organic amendments increase large macroaggregate formation and alter soil microbial communities.

6.2. Conservation Tillage and Residue Management

Conventional tillage practices disturb the soil significantly, affecting its physical, chemical, and biological properties, as they break soil structure, promote a negative soil-water balance, reduce biodiversity, and expose soil to solar radiation. Conventional tillage systems are prone to soil erosion, especially in areas with sloping land. The widespread use of conservation tillage has been accepted as a fundamental way to improve soil health and mitigate soil degradation (Sainju et al., 2003). The intensity of soil disturbance in conservation tillage is reduced compared with conventional tillage, while maintaining or improving the surface crop residue cover. Practices such as no-tillage, reduced tillage, mulch tillage, and controlled traffic systems are termed conservation tillage.

Returning crop residues to the soil improves the soil's physical and chemical properties and promotes the formation of soil organic matter. Decision support strategies are required to optimize the balance among crop residues left in the field, ditch cleaning, the cultivation of cover crops, the introduction of green manure crops, and the application of organic materials (Hiel et al., 2018).

6.3. Crop Rotation and Diversification

Crop rotation and diversification are essential practices for maintaining soil health and enhancing crop productivity (Polat, 2018). Crop diversification positively affects soil quality, increases resilience to environmental change, and contributes to food security. It mitigates soil erosion, enhances aggregation and organic carbon content, and supports diverse microbial communities. Crop rotations affect soil physical properties, nitrogen and carbon levels, greenhouse gas emissions, and several pest and disease dynamics (Yang et al., 2024). Diversification strategies have proven effective in smallholder farming systems, addressing food insecurity and climate-change adaptation. Implementing crop rotations and diversification strategies is vital for sustainable agriculture and long-term food security.

6.4. Nutrient Management and Fertilization Strategies

Soil nutrient management is an essential strategy to maintain soil functioning, fertility, and chemical health while ensuring sustainable crop production (Walia et al., 2024). Low soil fertility is a key constraint to crop productivity and is frequently exploited by the community, interactive soil degradation processes seriously impacting labour productivity, income, and food security of smallholders (Wani et al., 2015). Fertilization interventions and integrated

nutrient management mixing organic and inorganic sources provide greater productivity benefits where crop residues are otherwise removed and are a reasonable compromise for sustainable, less-wash-prone crop production and soil health status.

6.5. Biological Inoculants and Ecosystem Services

Biological inoculants are prepared microbial consortia or pure cultures with potential beneficial or lethal impacts on plants, pathogens, or other organisms (Mukhopadhyay et al., 2023). Soil may undergo multiple alterations in structure and composition as a result of climate shift. Plant growth-promoting microbes rapidly establish root–microbe interaction with just seed inoculation, moving with plant roots during soil disturbance (Omomowo & Babalola, 2019). Through phytohormone modulation, these bacteria can help restore the damage or boost the productivity of plants. Inoculating beneficial microorganisms directly into soil offers more comprehensive protection and management compared with indirect seed-inoculation methods (Singh et al., 2023).

6.6. Water Management and Irrigation Efficiency

Water is increasingly becoming a limiting factor for crop production, making the management of water resources an urgent priority. According to figures from the Food and Agriculture Organization (FAO), global fresh water consumption has increased in parallel to population growth. Agricultural uses constitute 70% of total yearly withdrawals, of which around 59% is actually consumed. In dry areas, however, irrigation withdrawals may reach over 95% of total demands. Currently, more than one-fifth of the world’s cultivated land is irrigated, and around 50% of the food supply is produced on irrigated lands. It is therefore essential to ensure that the most effective and sustainable water management practices are adopted (Greenwood et al., 1970). Water productivity—that is, the ratio of yield to water use—can be improved at all farming scales through a combination of technical and non-technical measures, including appropriate irrigation systems, efficient irrigation scheduling, crop agronomy, and soil water management.

7. Soil Health in Sustainable Crop Production Systems

Over the last few decades, the world has witnessed the intensification of agricultural ecosystems driven primarily by rising population, consumer demand, changing dietary habits, and urbanization. Such changes have increased pressure on cultivated soils resulting in the degradation of vital soil properties, impairing the capacity of soils to maintain and sustain agricultural productivity. Furthermore, market forces led to the increasing use of input-intensive cropping systems, causing imbalances that compromised both crop and soil health. In such a scenario, soil health has emerged as an important concept that integrates the condition of soil system components with their functioning, emphasizing the fundamental need for their protection and improvement. The soil ecosystem is composed of important physical, chemical, and biological components that define soil quality. Examples of complex processes such as water management—which is a climatic gradient-related issue—further

complicate the dilemma between soil and crop health. Over the years, a number of definitions of soil health has been offered but the most comprehensive definition is the ability of soil to function as a vital living system to sustain plant and animal health. The importance of soil health is further amplified under continued climate evolution, which deteriorates global food security (Jaster, 2010).

7.1. Agroecological Approaches and Resilient Farming

Intensive land and water management practices have contributed to significant global food production increases while concurrently degrading the ecosystem and threatening food security. Addressing these concerns, the ecologically driven agroecological approach—rooted in traditional agriculture yet adaptable to modern settings—has gained traction for fostering ecosystem resilience. Emphasizing low-input cropping systems, agroecology integrates soil health and crop diversity into its framework (Basch, 2017). Conservation Agriculture exemplifies this approach, aiming to enhance agricultural resilience through reduced soil disturbance, year-round soil cover, and crop rotation/diversification. Comprehensive adoption of these practices enables sustainability while augmenting soil health criterion (Cuevas et al., 2019).

7.2. Precision Agriculture and Soil Health Monitoring

Precision Agriculture (PA) as an emerging and sustainable system optimally manages crop commodities and farmland by maximizing production while minimizing economic costs and resulting negative influences on the surrounding environment. This is achieved by improving resource utilization through its key principles and technologies. Generally, PA starts from the construction of an Internet-of-Things (IoT)-based data collection system installed on equipment and at any location in farmland, enabling the prerequisite acquisition of big data. Then, cloud-based PA platforms are established to perform information storage and processing at scale, and subsequently facilitate optimization and prediction at virtually any future point in time. These developments lead to the provisioning of timely customized farming prescriptions generated through artificial intelligence (Kim & Lee, 2022). In parallel, many other complementary technologies supporting the development of eco-friendly farming methods have also been invented. These advances include the automation of most machinery, which lightens labour burdens and enhances uniformity and repeatability in operations; the construction of predictive crop growth and climate condition models via sensor-based monitoring; and the provision of completely new fertilization strategies exempt from organic components.

Effective management of soil characteristics in both field and controlled environments is of utmost importance to attaining the fundamental goals of PA (de Paul Obade & Gaya, 2021). Accordingly, various elevated sensing and sampling techniques for assessing important soil and crop properties have been developed, specifically targeting deficiencies in traditional assessment methods relying heavily on human visual inspection. In comparison with uncontrolled assessments, these elevated techniques aim to provide soil information and nutrient solutions to farmers at higher accuracy and shorter delay. Nevertheless, timely

monitoring of soil properties still remains highly challenging due to farmers' surging need for non-instantaneous yet accurate assessments. Systematic diagnostic techniques that leverage crop sap and nutrient solution rather than soil as the fundamental measurement matrix can alleviate this dilemma.

Building on precise soil health assessment at either the land- or plot-level, the cropping factor—which entails the ongoing effects of crop rotation and seasonal planting, rather than single batch planting at a specific time—is further investigated through preliminary modelling approaches, such as spatial matrix analysis. Based on this, simple classification models can effectively divide protective farming situations into three categories: comprehensive, partial, and nonprotection. Improved coding and grading techniques are applied further to represent the cropping factor for monitoring the cropping condition.

7.3. Climate Change Impacts and Adaptation for Soils

Sounding the alarm on the impacts of climate change is almost becoming clichéd. Nevertheless, agriculture will be profoundly affected by climate change in which soil is a crucial asset. Soil is a depleting resource due to erosion and this creates a wake-up call for soil adaptation. Climate change influences the soil through rising temperatures, elevated CO₂ level, altered rainfall variability, extreme precipitation patterns, increased drought situation, etc. All these factors increase the rate of erosion and degradation of soil (Daba, 2018).

Soil protection and conservation management should be a high priority since it determines sustainable crop production systems. Therefore, adaptation pathways to protect the soil are vital (Igwe et al., 2017). Sustainable agricultural practices and integrated cropping systems should be the fundamental design in maintaining soil health and sustainability. Active engagement and education of the farmers are also critical steps in providing better understanding and motivation to protect the soil. Creation awareness of educational campaigns to sensitize soil issues among farming communities should be promoted regularly. Moreover, retaining a clear and precise soil health management plan for each respective land units in cultivation offers highly regarded adaptation opportunity to sustain soils.

8. Socioeconomic and Policy Dimensions of Soil Health Management

Healthy soils are essential for sustainable development, human well-being, and economic welfare. Although the properties of healthy soil are well understood, implementing practices to achieve and sustain soil health remains a challenge. Current European policies—such as the Soil Thematic Strategy and the Common Agricultural Policy (CAP)—aim to conserve soils through standards like Good Agricultural and Environmental Condition (GAEC) but issues like water erosion persist. Measures such as minimum soil cover, appropriate land management, and maintaining soil organic matter are in place, yet practices often follow a 'business-as-usual' model. Broader adoption of Conservation Agriculture—no-till farming, crop diversification, and maintaining soil cover—is needed to improve soil

conservation. Institutional and policy support are essential to mainstream agro-ecological practices that enhance soil health, productivity, and ecosystem services (Basch, 2017).

Soil health is a key indicator of sustainable management, influencing human health and environmental quality. Increasing food demands and population growth will put more pressure on still-limited natural resources such as land, water, and energy. Current agricultural practices risk environmental pollution, resource depletion, and degradation. To ensure future sustainability, there is a need to develop production systems that rely less on non-renewable resources and more on renewable energy from the sun. Improving soil health is crucial for ecological intensification and meeting future food and energy needs. The condition of soils impacts air quality, water quality, and overall ecosystem health, making soil management vital for sustainability. An international workshop highlighted the importance of soil health as a primary measure of sustainable land use (Doran et al., 2002).

9. Future Research Directions

Probes into soil health management and crop production reveal significant knowledge gaps and avenues for further research. Healthy soil maintains ecological balance, plays a crucial role in crop farming, and is a key aspect of sustainability. It has various characteristics, including physical, chemical, biological and ecological properties, that are essential to food security. Monitoring nitrogen and other elements, as well as making predictions based on these observations, improves cost, use efficiency, crop production, water and fertilizer management (Walia et al., 2024). Urban sprawl encroaches on agricultural areas, a global phenomenon that also includes Pakistan. The challenge of forming an integrated approach arises from variables including, among many others, soils, climatic conditions, and crops grown.

The focus on soil health varies over time and as a function of the socio-economic scenario (Cuevas et al., 2019). Likewise, many technical recommendations are not founded on a thorough understanding of the interaction between soil forms and management practices on the one hand and ecological and productivity functions on the other. Integrated soil, crop and pest management that results in various services or products other than food is also an area reserved for exploration.

10. Conclusion

Sustainable agricultural systems support the needs of 9 billion people by 2050, improving food security, maintaining environmental quality, and enhancing soil health. Soils sustain crop production systems, thus soil health management and sustainable crop production mutually reinforce. The current scientific literature estimates the extent of soil health and soil health indices, describes the physical, chemical, and biological components of soil health, outlines soil health management practices, and examines components of sustainable crop production linked to soil health.

Conflict of Interests

None.

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