



Advance Techniques in Soil Health and Nutrient Management: A Comprehensive Review

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ABSTRACT

As a key practice that has developed through scientific and technological advancements, conservation agriculture, precision farming, organic farming, and integrated nutrient management are highlighted. Interdisciplinary collaborations between soil science, agronomy, biotechnology, microbiology, and environmental science are examined, showcasing their collective impact on soil management strategies. Traditional soil management practices, while effective, often lack the integration of interdisciplinary approaches necessary to address contemporary agricultural challenges. The research additionally examines how socio-economic and policy viewpoints support sustainable soil management techniques. Case examples and real-world applications are provided to highlight the useful advantages and results of these cutting-edge techniques. In order to further optimize crop production and soil management, the review highlights present issues and suggests future research avenues. The implementation of integrated nutrient management (INM) strategies, such as adding organic soil amendments in addition to fertilizer, has demonstrated benefits for preserving and restoring soil quality, which in turn reduces overuse of fertilizer in agricultural areas. Thus, the impact of fertilizer and compost on broadacre crop yield and nitrogen usage efficiency (NUE) was contextualized in this review. The results highlight the need for a comprehensive strategy that incorporates environmental, socioeconomic, scientific, and technical aspects in order to create sustainable agricultural systems.

Keywords: Agricultural policy; soil management; crop production; biotechnology; conservation agriculture; soil health.

1. INTRODUCTION

For agricultural systems to be sustainable and for crop output to be maximized, soil health is essential. It includes all of the physical, chemical, and biological characteristics of soil that work together to determine how well it supports plant growth, functions as a living ecosystem, and offers necessary ecosystem services. Robust crop yields depend on healthy soils because they improve root development, water retention, and nutrient availability. The fact that over 95% of food production worldwide depends on soil highlights the significance of soil health (FAO, 2015). Food security and agricultural productivity are directly threatened by soil health degradation, whether it is from pollution, nutrient depletion, or erosion. Approximately 33% of the world's soils are already deteriorated, impacting an estimated 2 billion hectares of land, according to the UN (Gomiero, 2016; UNCCD, n.d.). It is commonly known that crop yield and soil health

are related (Hijbeek et al., 2017; Yadav et al., 2019). One study by Lal, (2004) shows, for example, that increasing soil organic matter by 1% can boost wheat yields by 0.1–0.2 tons per hectare. According to a thorough assessment by Schjønning et al., (2018), well-managed soils with better structure and a greater organic matter content improve water infiltration and storage, which increases crop resilience during droughts. Additionally, the biodiversity of soil, which includes microorganisms like fungi and bacteria, is essential to plant health and nutrient cycling. According to a study by Peralta et al., (2018), Trivedi et al., (2018), a variety of soil microbial communities improve plant disease resistance and nutrient availability, which greatly increases agricultural output. Two essential elements of long-term agriculture are nutrient control and soil health. Plant growth (Gomiero, 2016; UNCCD, n.d.), crop yield (Hijbeek et al., 2017; Yadav et al., 2019), and environmental sustainability (Lal, 2004; Schjønning et al., 2018) are all directly

impacted by the quality of this ecosystem, which is the living habitat that forms the basis for agricultural production (FAO, 2015). In order to preserve soil fertility and prevent fertilizer overuse, which can have negative environmental effects, proper nutrient management is essential (Peralta et al., 2018; Trivedi et al., 2018). In order to support profitable and ecologically conscious agriculture, this chapter explores the importance of soil health and the best nutrient management techniques (Trivedi et al., 2018; Trivedi et al., 2017).

Centuries of practical knowledge and experience have led to the development of traditional soil management techniques, which have long formed the foundation of agriculture (Trivedi & Gautam, 2017; Araya-Alman et al., 2020). The major goal of these activities is to prolong crop output by preserving the fertility, structure, and general health of the soil. The most widely used conventional methods for managing soil include tillage, crop rotation, cover crops, and the use of organic amendments like compost and manure (Calero et al., 2022; Gautam et al., 2017). For example, planting a variety of crops in the same place throughout a series of growing seasons is known as crop rotation (Olivares et al., 2022a; Campos, 2023; Trivedi & Gautam, 2019). This method breaks the cycles of pests and illnesses, controls soil fertility, and lessens soil erosion. According to a lengthy study by Olivares et al., (2022b), crop rotation can greatly increase soil organic matter and nitrogen cycling, which will increase crop yields. In particular, it has been demonstrated that switching up the legumes and cereals naturally raises the soil's nitrogen content, which lessens the requirement for synthetic chemicals (Suman et al., 2020). On the other hand, cover crops like rye, vetch, and clover are sown in the off-season when the land may otherwise be left naked. These crops boost the amount of organic matter in the soil, enhance its structure, and prevent soil erosion. Cover crops can raise soil organic carbon levels by up to 0.5 tons per acre annually and prevent soil erosion by up to 90%, citing a study by Trivedi et al., (2020). Furthermore, cover crops can improve water retention and infiltration, which will improve crop resilience and root growth (Trivedi & Gautam, 2019).

2. EFFECTS OF VARIOUS SOIL TYPES ON MANAGEMENT TECHNIQUES

Agricultural results and soil management strategies are greatly influenced by the types of

soil that are present (Trivedi et al., 2020; Singh et al., 2021). Proper water management strategies is necessary to avoid compaction in clay soils, which are characterized by high water retention but poor drainage (Trivedi & Awasthi, 2020). Although they are fruitful, poor management practices can cause waterlogging, which lowers crop yields. Sand soils, on the other hand, drain rapidly and retain little water or nutrients, so they require regular irrigation and the addition of organic matter to enhance their structure (Gautam et al., 2020). In the absence of these measures, crops cultivated in sandy soils frequently experience drought stress and yield reductions. Because of their balanced texture, adequate drainage, and nutrient retention, loamy soils are thought to be perfect for agriculture (Rey et al., 2022). Loamy soils often yield large amounts of crops when they are properly managed for water and nutrients. Even though silty soils are rich in nutrients, erosion is a common problem. Contour plowing and cover crops are two important erosion management techniques that are necessary to stop soil loss, which would otherwise reduce their agricultural potential (Rodríguez-Yzquierdo et al., 2023). Liming and drainage systems are necessary to increase productivity in peaty soils, which are rich in organic matter but frequently acidic and poorly drained (Montenegro et al., 2021). Although waterlogging and acidity continue to be major obstacles, they can be extremely productive when correctly controlled.

3. EFFECTS OF NATURAL DISASTERS ON LAND USE AND SOIL MANAGEMENT

Natural catastrophes like hurricanes, earthquakes, wildfires, droughts, and floods seriously impair land use and soil management, especially on farms (Rodríguez et al., 2015). Flooding frequently causes waterlogging, nutrient depletion, and significant topsoil erosion, making it challenging for farmers to sustain crop productivity and restore soil health (Hernández et al., 2018a). Droughts cause compaction and decreased fertility by increasing soil salinity and lowering moisture levels (Hernández et al., 2020). When organic matter is burned in wildfires, erosion increases and water infiltration decreases, which can harm the impacted lands' long-term productivity (Doran & Zeiss, 2000). Because they destabilize soils and reduce arable area, earthquakes cause landslides in hilly farming zones (Chen et al., 2018). Similarly, storm surges and strong winds caused by

hurricanes and cyclones lead to soil salinization and farmland devastation (Diacono & Montemurro, 2011; Batey, 2009). In order to lessen their effects, these occurrences collectively reduce agricultural productivity, necessitate intensive recovery efforts, and emphasize the necessity for resilient soil management techniques.

4. IMMEDIATE OBSTACLES IN THE WAY OF BETTER SOIL MANAGEMENT

Although we hear about abundant crops every year, we are nonetheless beset by the enduring problems of underdeveloped farmer income and starvation. Insufficient knowledge and comprehension of soil nutrient imbalances is frequently the underlying cause of this phenomenon (Bedano et al., 2011). These persistent issues are largely caused by differences in soil nutrients, even in the face of rising agricultural yields. One of the many urgent issues facing soil health are listed below,

Erosion of the soil: A serious danger to soil health is soil erosion, which can be caused by both wind and water. It causes topsoil, which is abundant in nutrients and organic matter, to disappear. Poor land management techniques, deforestation, and extreme weather events frequently make erosion worse.

Soil degradation: A wide range of processes, including erosion, compaction, salinization, and acidity, are included in the general phrase 'soil degradation'. The soil's capacity to sustain plant development is diminished by these processes, which may result in a decline in agricultural output (Berendsen et al., 2012).

Decline of organic matter in the soil: The amount of organic matter in many soils is declining as a result of intensive farming, excessive use of synthetic fertilizers, and poor crop residue assimilation. Microbial activity, nutrient retention, and soil structure all depend on the organic matter in the soil.

Nutrient depletion: Nitrogen, phosphorus, and potassium are among the vital nutrients that are frequently lost from the soil as a result of intensive agriculture. This may lead to diminished crop yields and nutritional imbalances.

Soil contamination: Pollutant contamination of soil can result from mining, industrial operations, and the application of pesticides and herbicides. Hazards to human and environmental health can

arise from contaminants such as heavy metals and chemical residues, which can also damage soil health.

Loss of biodiversity: A wide variety of creatures, such as insects, fungus, bacteria, and earthworms, are found in soil ecosystems. This biodiversity can be disrupted by pollution, habitat destruction, and changes in land use, which can have an impact on nitrogen cycling and soil health in general (Bhardwaj & Sharma, 2013).

Climate change: By changing precipitation patterns, raising temperatures, and encouraging extreme weather events, climate change can make problems with soil health worse. These modifications may have an effect on carbon sequestration, microbial activity, and soil moisture (Brevik, 2009; Brivik, 2018).

Urbanization: Natural soil habitats and fertile agricultural land are frequently lost as a result of infrastructure development and urban area growth. Urbanization can decrease the amount of arable land available and disturb soil ecosystems.

Land conversion and deforestation: Valuable soils and their distinctive qualities may be destroyed when forests and other natural landscapes are turned into agricultural land. Particularly, deforestation can result in decreased soil health and increased erosion (Chen et al., 2018).

Poor soil management: Inadequate irrigation, excessive tillage, and the abuse of chemical inputs are examples of poor soil management techniques that can negatively impact soil health. In order to solve these problems, sustainable soil management techniques are essential.

Water shortage: In dry areas, water shortage can result in excessive irrigation and salinization, which further deteriorates soil health. To avoid these problems, effective water management is crucial.

5. DEVELOPMENTS IN SOIL MANAGEMENT TECHNIQUES

5.1 Conservation Agriculture

A revolutionary approach to soil management, conservation agriculture (CA) seeks to improve environmental protection, agricultural sustainability, and soil health (Hernández &

Olivares, 2020). The fundamental tenets of CA include varied crop rotations, permanent soil cover, and little soil disturbance (López-Beltrán et al., 2019; Magdoff & Van Es, 2000). CA reduces erosion, protects soil organic matter, and maintains soil structure by minimizing soil disturbance. When seeds are sown into undisturbed soil, no-till techniques can reduce soil erosion by up to 90% in comparison to conventional tillage (Trivedi et al., 2020). There are several benefits to using cover crops, crop rotation, and no-till for sustainable agriculture (Singh et al., 2020). No-till farming improves soil fertility and water retention by preserving soil structure and increasing soil organic carbon (Trivedi et al., 2019; Trivedi, 2019).

5.2 Precision Agriculture

Precision agriculture (PA) adapts farming methods to the particular circumstances of each location by utilizing cutting-edge technologies such as the Geographic Information System (GIS), Remote Sensing, Global Positioning System (GPS), and data analytics. GPS pinpoints precise positions, GIS combines this spatial data to map field variability, and remote sensing uses drones and satellites to in real-time monitor crop health, soil moisture, and fertilizer distribution (Trivedi & Awasthi, 2021). Additional information about soil characteristics, such as texture, pH, nutrient levels, and organic matter content, is provided by soil mapping. Variable Rate Technology (VRT) uses this information to apply inputs, such as water, fertilizer, and pesticides, precisely where they are needed, maximizing resource use and minimizing environmental impact (Trivedi et al., 2020).

5.3 Organic Farming and Agroecology

Sustainable soil management techniques like organic farming and agroecology place an emphasis on biodiversity preservation, soil health, and environmental stewardship. By avoiding synthetic inputs like pesticides, fertilizers, and genetically modified organisms, organic farming promotes natural alternatives including crop rotation, compost, and cover crops to improve soil fertility and control pests (Katkani et al., 2021). Additionally, it seeks to increase soil organic matter and biological activity, both of which enhance soil structure and nutrient cycling (Trivedi et al., 2022). In contrast, agroecology concentrates on biodiversity, nutrient cycling, and

ecosystem resilience while applying ecological concepts to agriculture.

5.4 Nano Concept Biochar

A promising soil amendment is biochar, a stable form of carbon created by pyrolysis, the thermal breakdown of organic material under low oxygen conditions (Trivedi & Gautam, 2022). Applying biochar to soils improves nutrient availability, cation exchange capacity, and water retention, all of which increase soil fertility. More microbial activity and nutrient retention are made possible by its porous nature, which may lessen the requirement for artificial fertilizers. Furthermore, because biochar can store carbon in soils for hundreds to thousands of years, it is being investigated more and more as a method for carbon sequestration, which helps to mitigate the effects of climate change (Verma et al., 2023).

5.5 Cross-slope Cultivation

Instead of following up and down slopes, cross-slope farming, sometimes referred to as contour farming, is an erosion management technique in which agricultural operations are in line with the landscape's natural contours (Nandeha et al., 2023). By slowing down water flow, increasing water infiltration, and minimizing topsoil loss which is essential for preserving soil fertility this technique dramatically lowers soil erosion (Yadav et al., 2023). Particularly in steep or sloping areas, farmers can improve water use efficiency and preserve moisture by plowing, planting, and cultivating in accordance with the land's contours (Gautam et al., 2023).

5.6 Integrated Nutrient Management

A comprehensive approach to soil fertility, Integrated Nutrient Management (INM) combines organic and inorganic nutrients to improve agricultural yields, nutrient efficiency, and environmental stewardship. INM promotes the thoughtful application of inorganic fertilizers in conjunction with organic inputs such as manure and compost to address the unique nutrient requirements of crops and adjust to soil conditions. Nutrient balance, enhanced soil health, and long-term agricultural productivity are the goals of this approach (Trivedi et al., 2023). INM promotes environmentally friendly farming methods, strengthens soil organic matter, and fills nutrient deficiencies by combining different nutrient sources (Yadav et al., 2023).

5.7 Nutrient Management Practices

Balanced fertilization: Applying the right nutrients in the right amounts is essential. The 4Rs approach (Right source, Right rate, Right time, Right place) ensures efficient nutrient use.

Organic matter management: Incorporating organic matter through crop residues or organic amendments enhances soil health. It improves soil structure, water retention, and nutrient availability.

Crop rotation: Crop rotation helps break pest and disease cycles and can improve nutrient management by diversifying nutrient demands.

Crop cover: Planting cover crops between cash crops or during fallow times can help to improve the health of the soil. They improve organic matter, fix nitrogen, and prevent erosion.

Reduced tillage: Lowering tillage reduces soil disturbance and preserves soil structure, both of which are critical for soil health.

Technologies for Nutrient Application: Applying nutrients with accuracy ensures uniform distribution, minimizing overuse and environmental effect (Nandeha et al., 2024; Kumar et al., 2024).

6. ISSUES AND ALTERNATIVES

Water contamination due to nutrient runoff: Overuse of nutrients can result in nutrient pollution. Fertilizers with controlled release and precise nutrient management can help to lessen this problem.

Erosion of the soil: Erosion weakens the soil and depletes topsoil. Terracing and contour farming are two conservation techniques that might lessen erosion.

Degradation of the Soil: Intense farming methods and continued monoculture can cause soil degradation. Restoring soil health can be aided by the implementation of crop rotation and organic matter management.

6.1 The Effects of Advanced Soil Management Techniques on the Economy

The economic impact of advanced soil management techniques on agriculture and society is substantial. Using conservation, integrated nutrient management, and precision

agricultural techniques can increase crop yields, lower input costs, and boost farm profitability (Agrawal et al., 2024). Techniques like cover crops and reduced tillage help to conserve water, limit soil erosion, and cycle nutrients, which lowers production risks and improves resource use efficiency (Kumar et al., 2024). In rural areas, sustainable soil management techniques can encourage economic diversification by creating new markets for certified organic products, carbon credits from soil carbon sequestration, and payments for ecosystem services (Gupta et al., 2024; Kumar et al., 2024).

6.2 Policy's Function in Advancing Sustainable Soil Management

In order to promote sustainable soil management, effective policies are essential. Governments encourage farmers to adopt sustainable practices and apply soil conservation measures by enacting land-use restrictions, criteria for soil quality, and incentives for doing so (Haldkar et al., 2024). Farmers' adoption and investment in soil health is also greatly aided by government grants, subsidies, and tax incentives for sustainable techniques including organic farming, agroforestry, and cover crops (Trivedi et al., 2024). Furthermore, policies that support farmer education, extension services, and platforms for knowledge sharing greatly increase grassroots awareness and adoption of sustainable soil management techniques (Nandeha & Kewat, 2018).

6.3 International Policies for Soil Conservation

Enhancing financial and technical support for sustainable land management methods, especially in developing nations, should be the main goal of international policy recommendations for soil protection. For instance, by promoting the adoption of sustainable soil management techniques at the local level and assisting national soil information systems, the FAO's Global Soil Partnership (GSP) works to enhance soil governance (Trivedi et al., 2020). The preservation and repair of terrestrial ecosystems, particularly soils, is another priority of UN SDG 15. Incentives for conservation agriculture techniques, investment in regenerative agriculture, and the promotion of carbon credits for soil sequestration are among the suggested courses of action (Nandeha et al., 2016). To guarantee long-term sustainability, cooperative international frameworks that

connect soil health to more general climate and food security objectives ought to be reinforced.

6.4 Current Challenges in Implementing Advanced Soil Management Practices

A number of formidable obstacles stand in the way of the broad acceptance and efficacy of sophisticated soil management techniques in a variety of agricultural systems. First off, high upfront expenditures and insufficient infrastructure, especially in environments with limited resources, continue to hinder the adoption of cutting-edge technology like remote sensing, soil sensors, and precision agriculture tools (Nandeha et al., 2016). Second, there is a significant knowledge and awareness gap about the advantages and appropriate application of these approaches among farmers and stakeholders. Adoption is further hampered by limited access to training, information, and extension services. Thirdly, scaling up these techniques is significantly hampered by inconsistent policies, lax regulatory frameworks, and a lack of institutional backing. In order to encourage adoption and guarantee long-term results, it is imperative to achieve policy coherence and create institutional frameworks that support it (Nandeha et al., 2017).

6.5 Prospective Developments and Innovations in Soil Management Technology

Technological developments have the potential to transform sustainable agriculture methods, which bodes well for the future of soil management. Predictive models that evaluate crop performance, weather trends, and soil health metrics in real-time are made possible by artificial intelligence (AI) and machine learning (ML) (Sahu et al., 2017). Farmers can make data-driven decisions by integrating sensor technology and Internet of Things (IoT) devices to enable continuous monitoring of soil health indicators like moisture levels and nutrient content (Sahu et al., 2015). By using precision agricultural techniques, such as variable rate application (VRA) of nutrients and fertilizers based on soil variability maps, nutrient use efficiency is increased while environmental consequences are reduced (Kumar et al., 2017). Enhancing soil fertility and water retention capacity, nanotechnology holds promise for fertilizer delivery systems and soil remediation (Chen et al., 2018). Climate-smart techniques

that improve soil structure and biodiversity while reducing climate risks include agroforestry and the use of biochar (Gomiero, 2016). By guaranteeing accountability from farm to fork, blockchain technology has the potential to improve agricultural practices' transparency and traceability (Bedano et al., 2011). It will take teamwork to overcome technical, financial, and regulatory obstacles in order to adopt these developments and guarantee resilient and sustainable soil management techniques over the world.

7. CONCLUSION

In order to maximize crop output through interdisciplinary approaches, this review has summarized recent developments, difficulties, and potential paths forward in soil management techniques. Important conclusions stress the interdependence of biological, chemical, and physical soil characteristics and the vital role that soil health plays in agricultural sustainability. Carbon sequestration, water efficiency, and soil fertility are all being improved by cutting-edge techniques including integrated nutrient management, precision farming, and conservation agriculture. It is essential to address issues including knowledge gaps, policy inconsistencies, socioeconomic effects, climate variability, and technology obstacles. Longitudinal studies, incorporating cutting-edge technologies like artificial intelligence and nanotechnology, and investigating socioeconomic factors affecting adoption rates should be the main objectives of future study. Scaling up sustainable practices internationally requires strong institutional support and effective policy frameworks. The advancement of agricultural resilience and food security depends on the multidisciplinary integration of soil science, agronomy, biotechnology, and environmental sciences. This ensures that creative soil management techniques maintain and improve productivity while reducing environmental effects. The foundation of sustainable agriculture is the management of nutrients and the health of the soil. Long-term food security and environmental preservation depend on maintaining healthy soils through conservation measures, organic matter management, and balanced fertilization. By comprehending the soil ecology and putting best practices into practice, farmers can guarantee sustainable and productive agriculture for future generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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