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REVIEW

Integrating Emerging Technologies and Eco-Friendly Materials for Soil Health and Environmental Resilience

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ABSTRACT

Soil is the basic component of the ecosystem responsible for life. The quality of the soil or soil health is the driving force in the ecosystem. Globally with changing climatic scenario, soil health is greatly affected thus having a greater impact on the agriculture and food production. Attributes like physico-chemical and biological properties of soil determine the status of the soil health. Although, several impacts pertaining to the climate change, unsustainable farming practices, overuse of agrochemicals have led to the depletion of the soil quality. A multifaceted approach is required for conserving and enhancing soil productivity by means of integrating conventional knowledge with modern technology. Modern technologies and concepts like precision agriculture, site-specific nutrient management are gaining importance due to accurate and immediate decision making ability by optimizing input use, enhancing nutrient management, and supporting

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environmentally sustainable practices. These tools rely on data-driven techniques to monitor and manage soil conditions effectively, thereby promoting soil fertility and reducing ecological harm. Nanotechnology is the other concept giving a promising results under the emerging innovations. Soil fertility that includes the plant growth, nutrient availability and diversified microbial population has improved by application of nanomaterials. Despite these advancements, challenges persist in the widespread adoption of soil health monitoring technologies, including remote sensing and smart sensors. Issues such as limited spatial resolution, inconsistent ground-truth data, and the requirement for specialized skills continue to hinder long-term monitoring efforts. The challenges in adoption of the technologies are due to a lack of skill and high installation costs.

Keywords: Soil Health; Sustainable Agriculture; Precision Agriculture; Nanotechnology; Remote Sensing

1. Introduction

Soil is an imperative material consisting of stratified combinations of mineral, water, air, organic matter and infinite living organisms from microbes to earthworms which form the base for the terrestrial life. Healthy soil performs a multitude of essential functions like ensuring flora and fauna, governing water filtration and pollutants buffering, nutrients recycling and providing physical stability. Soil health is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA-NRCS). A lengthier version of the definition is the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health [1]. Soil health is the crucial indicator of the vitality and sustainability of terrestrial ecosystems which functions as a living ecosystem by assuring the flora and fauna, also encompasses all the three important properties viz., physical, chemical and biological to improve the productivity [2,3]. A comprehensive approach to soil management was brought into limelight by the scientists in the past 20th century depicting that soil is a vast material where all physical, chemical and biological properties are interconnected which helps in maintaining or enhancing the soil health [4,5]. The idea of soil health has evolved over time to encompass a greater comprehension of the capacity of the soil to function as a life-supporting system, encouraging plant growth, controlling water flow, and filtering contaminants [4]. The concept of productive soils is relevant to global climate change and food security [6].

United Nations proposed 17 Sustainable Development Goals (SDGs), of which Goal 2 focuses on zero hunger that is interlinked with the development of international policy agreements and efforts for maintaining soil health. Assuring sustainable food production systems and putting into practice persistent agricultural techniques that boost output and productivity, support ecosystem maintenance, enhance ability to adapt to climate change, extreme weather conditions and other disasters which gradually increase the soil quality [7]. The Paris Climate Agreement (2015) acknowledges soil as a crucial carbon sink and highlights its role in mitigating climate change through improved soil management. On the contrary, the idea of soil health, which first appeared in the early 2000s, is still developing today, reflecting the intricate complexity of soil ecosystems [8]. The soil health is evaluated through wide variety of structural, compositional and microbial attributes related to the soil ecosystem activities, water management, nutrient cycling and diversified microbe population.

The global picture of soil health is concerning, with widespread degradation posing significant threat to food security, biodiversity, and climate change mitigation. UNESCO warns that 75% of the planet's soils are already degraded, directly impacting 3.2 billion people. If current trends continue, this proportion could rise to a staggering 90% by 2050.

Soil health in India plays a crucial component in ensuring national food security. However, it is subject to a variety of challenges shaped by the country's diverse soil types, climatic variability, and heterogeneous farming systems. The ongoing decline in soil quality driven by nutrient exhaustion, excessive chemical inputs, and soil erosion poses serious risks to agricultural output and ecological balance. The Indian subcontinent, possessing extensive agricultural area and a substantial population, encounters significant issues concerning soil health.

According to the National Bureau of Soil Survey and Land Use Planning, approximately 146.8 million hectares (around 30%) of India's soil is degraded. The Desertification and Land Degradation Atlas of India (2021) indicates this to be 97.85 million hectares (29.77% of geographical area) in 2018–2019.

The Indian soils possess several nutrient deficiencies due to inappropriate use of fertilizers as a result of green revolution, nutrient mining and soil erosion driven by natural and anthropogenic factors [9,10]. The SOC content in Indian soils is critically low, often below the threshold needed for healthy soil, which affects soil structure, fertility, and its ability to sequester carbon [11].

Goals of ecological sustainability in relation to soil health focus on maintaining soil fertility and structure while preserving biodiversity and minimizing degradation, ensuring long-term productivity and environmental balance, as shown in **Figure 1.**

Figure 1. Goals of ecological sustainability in relation to soil health.

2. Soil Health: Concepts and Indicators

The sustainable ecosystem and improved agricultural productivity are indicated by the soil health through various soil indicators, microbial community dynamics, and soil enzymes in relation to essential soil properties such as organic carbon content, bulk density, and soil pH.

Soil health is a comprehensive expression of the relevant soil physical, chemical, and biological properties (**Figure 2**). Soil health degradation is "the loss of the intrinsic physical, chemical, and/or biological qualities of soil either by natural or anthropogenic processes, which result in the annihilation of important ecosystem functions" [12].

The impact of traditional agricultural practices, particularly conventional tillage, on soil structure and physical properties, while advocating for conservation tillage practices that can improve soil health by reducing bulk density and enhancing water and nutrient transfer, ultimately influences plant growth and ecosystem resilience. A fertile or nutrient-rich soil is regarded as a dynamic living system that can support biodiversity, improve or maintain the quality of the air and water, control nutrient availability, build up soil carbon, support plant and animal health and productivity, and lessen erosion, among other advantages for ecosystems. Crop health and productivity, as well as sustainable agriculture, are based on healthy soil. Soil health information links stakeholder needs, agricultural laws, and sustainable produce management. Sustainable agriculture's objectives now include maintaining or improving environmental factors, such as climate change, and human health in addition to agricultural production based on nutrient management. Soil is potent living system that supports terrestrial life through its ability to sustain biological productivity, promote environmental quality, and support plant and animal health. Unlike the static term "Soil Quality" encompasses both agronomic productivity and ecosystem services. Modern agriculture and land-use practices necessitate a meticulous understanding of soil health indicators to ensure long-term sustainability[1]. Soil health indicators are presented in **Figure 3**, while their ecological implications are summarized in **Table 1**.

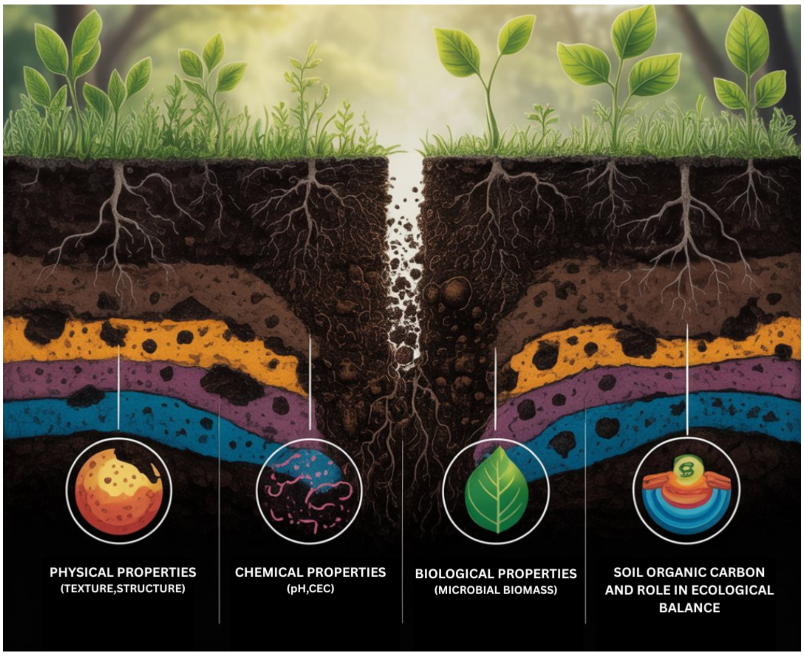

Figure 2. Soil Health: Concepts and Indicators.

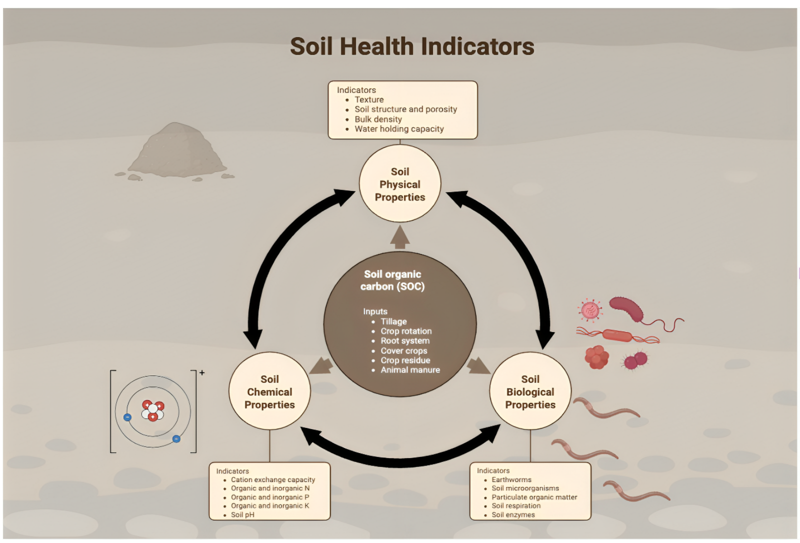

Figure 3. Different types of Soil Health Indicators.

Table 1. Ecological implications of Soil health indicators.

Indicator Category	Specific Indicator	Function in Soil Health	Ecological Implications	Source
Physical	Texture (sand, silt, clay)	Determines water retention, aeration, root depth	Influences plant water use, erosion, and soil biodiversity	Cardoso et al. [13]
	Structure (aggregate stability)	Affects water infiltration, resistance to erosion	Enhances productivity, microbial habitat, and resilience to compaction	Doran & Zeiss [1]
	Porosity	Controls air/water movement, microbial colonization	Boosts drought resistance, nutrient cycling, and soil respiration	Chahal et al. [14]
Chemical	pH	Influences nutrient solubility and biological activity	Modulates species composition, acidification, and microbial function	Karlen & Stott [15]
	CEC (Cation Exchange Capacity)	Represents nutrient-holding potential	Determines buffering capacity, nutrient loss risk, and fertility status	Kibblewhite et al. [16]
	Nutrient Availability (N, P, K)	Essential for crop productivity and plant-microbe interactions	Supports food web, biomass yield, and ecosystem stability	Allen et al. [17]
Biological	Microbial Biomass	Reflects biological productivity and nutrient transformation	Influences soil respiration, disease suppression, and carbon cycling	Pankhurst et al. [18]
	Enzymatic Activity (dehydrogenase, etc.)	Catalyzes nutrient turnover and organic matter decomposition	Indicates biological stress or resilience, links to organic matter processing	Alkorta et al. [19]
Cross-domain	Soil Organic Carbon (SOC)	Stores energy, enhances aggregation, and microbial habitat	Critical for carbon sequestration, erosion control, nutrient buffering, and climate regulation	Chahal et al. [14]

2.1. Structural Attributes of Soil Health

2.1.1. Soil Texture and its Implications

The relative proportions of sand, silt and clay particles which affect the water flow & storage, aeration, nutrient and contaminant adsorptive capacity, ease of tillage are referred to as a soil texture which is a major character that decides the soil quality [20]. It influences microbial activity, promotes root development, and affects the soil's capacity to hold onto water and nutrients all of which are crucial for conserving soil fertility and productivity.

The four soil health indicators are evolved NH_3, evolved CO_2, active fraction of available N, and soil organic matter (SOM) which are usually affected by the soil texture. Research revealed the impact of soil texture on soil health indices in agricultural soils in Ontario, underscoring the difficulties in implementing consistent soil health paradigms in various geographical locations and soil types. The evaluation of soil health and productivity management was simplified through the 3-category classification *viz.,*coarse, medium and fine as it offers more scope for easy understanding and on field decision making even by the non-experts. Soil mapping is made easy with the three-category classification making it more efficient and less complex [21]. Precision agriculture requires the clear and concise data for accurate results that are acquired by five group classification of soil *viz*., sand, sandy loam, light loam, medium loam, and clay which helps in unique soil management practices for each textural class across variable depths and regions. The association of soil textural classes mentioned in the five group classification with various soil attributes gives a clear picture in framing up the unique soil management practices [22,23]. The fertile soils offer optimal conditions for root development and nutrient availability other than moisture and nutrition retention which are affected by the soil texture [24]. Loamy soils are combination of sand, silt and clay particles which offer high moisture retention, high field capacity due to diversified macro and micro pores making them unique from the other soils supporting the plant growth and soil sustainability. Soil management practices are mostly recommended by understanding the textural class from the soil texture triangle which explains the water permeability and retention, leaching losses [25,26]. Sand particles are low in surface area thereby they cannot bind the organic matter (essential carbon and nitrogen) which has negative effects on the microbial activity and faster decomposition [27]. Soil texture determines the binding and releasing of the nutrients. The high cation binding capacity is observed in clayey soil compared to sandy soils thereby affecting the micronutrient efficiency management and holistic nutrient profile of the soil [28].

Texture is only the basic component of the soil health but not the sole determinant, other factors like land use history, climate and management tactics play an imperative role. For illustration, the effective soil conservation strategies vary based on the interaction between soil texture and climatic conditions [29].

2.1.2. Soil Structure and Porosity

Soil structure refers to the spatial organization of soil particles, pores, and organic components, which significantly influences various soil functions and processes. It is a dynamic property that varies with time due to natural and anthropogenic factors, affecting soil health and its ability to support plant growth, water infiltration, and other ecological functions.

Enhancing soil form is one major aspect of the complex process of improving soil health, which is essential for environmentally conscious farming and sustainable practices. Water retention, nutrient cycling, and carbon sequestration are all impacted by soil structure and are essential for preserving soil health. Use of ecological farming practices, incorporation of organic matter fosters the soil structure by boosting carbon sequestration and also aids in mitigation of climate change [30].

Soil porosity refers to the volume of pores or spaces within the soil, which affects its capacity to hold air and water, crucial for plant roots and soil microorganisms. The application of organic materials, such as compost and manure, further enhances soil porosity and aggregation, preventing soil crust formation [31]. Alteration of pore structure by biochar application favors in improved porosity and water retention. This is particularly evident with higher biochar application rates, which result in a broader pore size distribution and increased air-filled porosity [32].

Water and nutrient retention are essential for plant growth and increased porosity allows for better water infiltration and storage, reducing runoff and erosion [33]. Adequate porosity ensures sufficient air space for root respiration and microbial activity, which are vital for nutrient cycling and soil health [30,34]. Soil structure is influenced by the porosity by affecting its stability and resistance to compaction. Well-structured soils with optimal porosity support healthy root systems and reduce the risk of soil degradation [35]. Different agricultural practices like conservative agriculture which includes no tillage, crop residue retention, and crop rotation, lead to improvements in soil structure, porosity, and pore size distribution over a period of six to ten years, enhancing soil health and physical properties while also increasing soil organic carbon concentration. Studies reveal that soil under zero tillage (ZT) exhibits the lowest porosity compared to conventional management practices, which show the highest porosity and maximum connected pores, highlighting the significant differences in soil physical properties between CA and conventional agricultural methods [33].

2.2. Soil Organic Carbon and its Role in Ecological Balance

Soil Organic Carbon (SOC) is one of the main pillars in determining soil health and in maintaining ecological balance. The SOC affects various soil properties and functions, contributing to ecosystem activities such as climate regulation, soil fertility, and biodiversity. SOC acts as a major carbon reservoir, significantly larger than the atmospheric and biotic carbon pools, and is integral to the global carbon cycle. This makes it a key player in mitigating climate change and enhancing soil productivity.

The SOC improves the structure and increases in porosity influence the moisture & nutrient retention capacity vital for spike in plant growth and agricultural productivity [36,37]. The presence of SOC improves soil structure by promoting the formation of soil aggregates, which enhances soil stability and reduces erosion [38]. SOC and soil organic nitrogen are closely related which has a direct impact on soil productivity as it is a crucial nutrient for biomass production. It also plays a crucial role in the carbon cycle, serving as a source and sink of carbon and aiding in the sequestration of atmospheric CO_2, which helps to mitigate climate change [38,39]. The reduced emission of greenhouse gases is to be achieved by stabilizing SOC in soils through effective management of factors like soil type, climate, and land management practices which enhance SOC storage [37].

Microbes are harboured by SOC which contributes to nutrient cycling and conditioning of soil health [40]. The decline in the SOC levels is due to shifting or conversion of the forest cover into agriculture. Ecofriendly management practices, including the use of organic compost and reduced soil disturbance, can help maintain or increase SOC levels [37]. Understanding the topography, climate and soil properties which influence the SOC dynamics is crucial for designing effective land management strategies [41,42].

While SOC is crucial for ecological balance, its management poses challenges due to its dynamic nature and sensitivity to environmental changes. Anthropogenic activities can either enhance or deplete SOC levels, impacting its role as a carbon sink. Therefore, sustainable management practices are essential to harness the benefits of SOC for climate regulation and soil health. Additionally, ongoing research and policy initiatives are vital to address the complexities of SOC management and to promote practices that enhance its ecological functions.

2.3. Chemical (pH, CEC, nutrient availability)

The compositional properties such as pH, cation exchange capacity (CEC), and nutrient availability are the main indicators of soil quality, impacting its capacity to sustain and promote plant development ecosystem functions. These chemical indicators interact with physical and biological properties to determine soil fertility and productivity. Understanding these interactions is essential for sustainable soil management and agricultural practices.

2.3.1. pH (Power of Hydrogen ions)

Soil pH is a critical determinant influencing a wide range of biological, chemical, and physical processes that are essential for plant growth and ecosystem sustainability. It affects microbial activity, enzyme efficiency, and nutrient availability, making it a "master soil variable" [43]. The pH has a greater impact on nutrient availability, as it affects both soil reactions and plant uptake. For instance, increasing pH can decrease the availability of certain nutrients like phosphate, while increasing the availability of others like molybdate [44]. Optimal pH levels are necessary for maintaining a balanced ecosystem, as extreme pH levels can lead to nutrient deficiencies or toxicities, affecting plant growth and soil biodiversity [45].

2.3.2. Cation Exchange Capacity (CEC)

The capacity of the soil to adsorb the cations like Ca^{2+}, Mg^{2+} is an imperative indicator of soil health, reflecting the soil's ability to retain and exchange nutrient ions, which is integral for plant growth and soil fertility. It serves as a key metric for assessing soil quality, particularly in agricultural and natural ecosystems which are impacted by various factors, including soil texture, organic matter content, and the presence of clay minerals [45]. High CEC values indicate a greater capacity to hold essential nutrients, which can enhance soil fertility and plant growth. Conversely, low CEC can lead to nutrient leaching and reduced soil fertility.

Cation Exchange Capacity (CEC) of sandy soils in the forest agro-ecosystem significantly increases due to forest cover, which enhances fertility of the soil through the replenishment of biodegradable matter from diverse plant debris. This increase in CEC is influential for improving the soil's ability to retain and exchange major essential nutrients for plant growth [46].

2.3.3. Nutrient Availability

Sustainable agriculture practices mainly reflect on the supply of essential nutrients for the plant growth. Soil health is a multifaceted concept encompassing physical, chemical, and biological characteristics that collectively determine the soil's ability to function as a living ecosystem. Nutrient availability, particularly of nitrogen (N), phosphorus (P), and potassium (K), plays a significant role in assessing soil health, as it directly impacts plant growth and productivity. The fertility of the soil is determined by availability of nutrients and is influenced by factors such as soil pH, CEC, organic matter content, and microbial activity [45]. The availability of nutrients like nitrogen, phosphorus, and potassium is essential for plant growth and productivity. Fostering soil health through nutrient cycling and retention by nurturing the soil [47]. Soil microbes serve as indicators in shaping soil nutrient cycling processes by understanding their response to the nutrient additions which help in enhancing soil health and productivity. Addition of phosphorus significantly influences the soil bacterial community composition which aids in maintaining biodiversity and ecological function in temperate ecosystems [48]. Enhanced nutrient availability and soil health are achieved through the organic amendments like bokashi and biochar. These amendments enhance nutrient cycling and microbial interactions, contributing to environmentally friendly soil management[49].

2.4. Biological Attributes

Microbial biomass and enzymatic activity depict the biological activity and health of soil ecosystems. For sustainable farming methods and ecosystem restoration, these indicators offer information on the cycling of nutrients, the breakdown of organic matter, and the general fertility of the soil. Incorporating these biological markers into evaluations of soil health can improve knowledge of soil function and guide improved land management techniques. The mineralization of essential nutrients particularly nitrogen and carbon is carried out by diversified microbial population and made available to plants[50,51]. Regenerative agriculture practices like cover cropping, biodegradable waste management improve the SOC, total N, and phosphorus, sulphur related enzymatic activity. This implies that these practices enhance the biological functions and vitality of the soil. Microbial biomass responds positively to regenerative agricultural practices, such as organic amendments and conservation tillage, which boost soil organic matter and nutrient availability[52]. Improved nutrient availability and soil structure are altered by higher microbial biomass in various cropping systems[51].

Soil Biochemical Activity as a Health Indicator

The organic matter decomposition and nutrient mineralization are the core indicators for maintaining the soil health. Enzymes such as dehydrogenase, urease, and phosphatases are involved in key soil processes which indicate the biological activity and soil health[53,54]. Soil enzymes like dehydrogenase, acid phosphatase, β-glucosidase, and urease are sensitive to altering soil conditions, making them reliable indicators of soil health and fertility[55]. The biochemical properties of the soil are influenced by soil pH, moisture, and temperature, which affect microbial activity and enzyme efficiency[43]. Soil management practices like addition of organic amendments and reduced tillage will improve or exhibit the high enzymatic activities in soils which reflects enhanced microbial activity and nutrient cycling[50,56]. Biological indicators can be constrained by soil classification, which should be considered when interpreting soil health scores. Adjusting assessments based on soil type can improve the accuracy and relevance of soil health evaluations[52]. The holistic understanding of soil conditions can be accomplished by conjunction of other soil health metrics.

3. Emerging Technologies Enhancing Soil Health

3.1. Precision Agriculture Tools

Precision agriculture technologies (PATs) have significantly enhanced soil health by leveraging resource use, improving soil nutrient management, and promoting sustainable agricultural practices. By using data-driven methods to monitor and control soil conditions, these technologies increase soil fertility and mitigate their negative effects on the environment. By integrating advanced tools such as remote sensing, IoT devices, machine learning, and metagenomics, PATs offer precise interventions tailored to specific field conditions, thereby enhancing soil quality and crop productivity. The contributions of various technologies in enhancing the soil health are discussed as follows:

Sensors, GPS, drones, and IoT-based soil monitoring; Variable rate technology (VRT)

The integration of advanced sensor technologies into soil health monitoring has been significantly optimized by providing the real-time data on various soil parameters that improve soil conditions. Soil health monitoring includes a range of technologies *viz*., IoT devices, nanotechnology, and remote sensing, each contributing uniquely to the understanding and management of soil health (**Figure 4**).

The research reports suggest that the integration of advanced sensor technology for monitoring soil pH, moisture, and temperature significantly escalates the crop growth conditions, leading to increased agricultural output while minimizing environmental impacts. The effectiveness of the sensor-based system in promoting sustainable agriculture through precise irrigation practices and maintaining optimal conditions for microbial activity and root development. An alert mechanism within the system notifies users of significant changes in soil conditions, facilitating timely crop management interventions and improving overall soil fertility[57]. SensorSuite, a low-cost IoT device, enhances precision agriculture with real-time soil health analysis using five sensors, capturing data on moisture, temperature, and pH levels, and providing reliable and accurate results through cloud-based analytics and solar-powered operation. High resolution images and data for precise surveillance of pests, soil conditions and plant health help in optimal use of resources. Manual sampling, laboratory testing are laborious and protracted processes making it difficult to take the immediate corrective action which affects the crop productivity. IoT-based soil nutrient monitoring and analysis system enables real-time data collection and analysis of key soil parameters such as nitrogen, phosphorus, potassium (NPK), moisture, and pH levels, which significantly improves the efficiency of soil management compared to traditional methods that are time-consuming and reliant on manual sampling. By integrating IoT sensors, cloud computing, and data analytics. The system generates pertinent data that improves crop management, reduces fertilizer overuse, and improves resource efficiency, ultimately leading to higher agricultural yields and more sustainable practices [58]. Variable rate technology (VRT) is efficiently used in application of Agri inputs like water, fertilizer, and pesticides more efficiently guided by GPS-based real-time data, reducing waste and minimizing environmental impacts such as nutrient runoff and greenhouse gas emissions [59]. The integration of GPS with GIS and remote sensing technologies enables the creation of digital soil maps. These maps offer comprehensive details on soil characteristics, which are essential for site-specific nutrient management and sustainable crop production [60]. Precision farming, utilizing GPS, sensors, and drones, significantly reduces adverse environmental effects by sparingly using insecticides, fertilizers, and water, leading to less waste and more efficient resource use [61]. The enactment of UAV-based remote sensing with soil metagenomics is proposed as a transformative approach for precision agriculture, enhancing resource efficiency and aligning with sustainable agricultural objectives by reducing environmental impacts and minimizing chemical inputs [62].

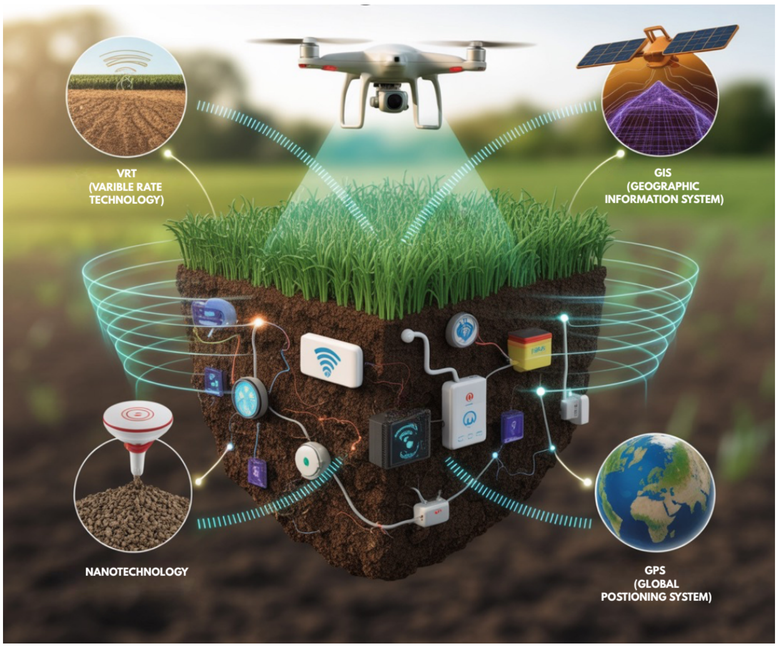

Figure 4. Emerging Technologies Enhancing Soil Health.

3.2. Nanotechnology in Soil Management: Nano Fertilizers and Nano Pesticides; Soil-Targeted Delivery Systems

Nanotechnology is a transformative tool in soil management, illustrating innovative concepts for soil remediation, fertility enhancement, and real-time monitoring. The high reactivity and mobility of nanoparticles can address various soil-related challenges, including salinity, nutrient management, and pathogen control by fostering agricultural productivity and promoting environmental sustainability.

By efficiently adsorbing, immobilizing, and degrading different contaminants like heavy metals, persistent organic pollutants, and resistant pesticides, nanotechnology shows great promise in soil remediation. This will address the degradation of soil quality and improve environmental sustainability. The application of nanomaterials improves soil structure by enhancing water retention, promoting aeration, and facilitating nutrient diffusion, while also enabling controlled-release capabilities of nano fertilizers that provide precise nutrient delivery to plants, ultimately boosting soil fertility and promoting plant growth [63].

The adsorption and degradation of soil contaminants is offered by the nanomaterials like nano zero-valent iron and metal oxides which provide a more efficient and targeted approach compared to traditional methods [63,64]. Nanoremediation techniques are eco-friendly and cost-effective, facilitating both *in situ* and *ex situ* applications to eliminate the soil contaminants [65].

Globally, Urbanization and agricultural expansion cause severe threat to the soil health through soil erosion, contaminants, and declining agricultural productivity. Improvisation of the affected soils through existing technological advancements is expensive and labor intensive thus failing to restore soil conditions to desired levels. When soils include nanomaterials (NMs), the effectiveness of rhizosphere microbes and other beneficial microbes improves the nutrient access for crops and supports better root system functioning and overall crop growth [66]. Nanomaterials such as zero valent iron, iron oxides, graphene oxide, and bimetallic nanoparticles are widely used for immobilizing heavy metals in soil and groundwater, demonstrating effective solutions for remediating heavy metal-contaminated sites and improving soil quality. Nanotechnology enhances agricultural sustainability by improving food production, nutrition quality, and overall agricultural practices, with nanomaterials also being utilized for antimicrobial properties in pesticides, biosensors, and fertilizers [64].

Nanoparticles enable the controlled and gradual release of nutrients, enhancing their availability to plants over time while minimizing leaching and runoff. In potato cultivation, foliar application of NPK nanofertilizers at just 50% of the conventional rate significantly improved yield, profit, and quality compared to traditional soil applications. This demonstrates the efficacy of nanofertilizers as an environmental friendly and efficient alternative to conventional chemical fertilizers [67]. The efficient use of essential plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which are currently used to enhance the soil through development of smart fertilizers and delivery systems by using nanotechnology in agriculture, specifically through the application of nanofertilizers and nanopesticides, which improves the solubility of active ingredients and enable slow or targeted release, thereby minimizing degradation and maximizing the effectiveness of these agricultural inputs [68]. Encapsulated nanoparticles absorb or bind pesticides and improve pesticide delivery by enabling targeted and controlled release directly onto plants and pests by reducing toxicity and environmental leakage while increasing pesticide efficacy. By adding ligands to bind to plant surfaces and creating pH-responsive nanoparticles, functionalization of nanoparticles improves pesticide targeting and controlled release, resulting in less pesticide use and a decreased risk of environmental contamination [69]. Nanotechnology significantly enhances agricultural practices by improving seed germination, root-shoot length, and seedling biomass, while also boosting physiological parameters such as nitrogen metabolism and photosynthetic activity in various crop plants. The application of nanoparticles in agriculture allows for reduced chemical usage, increased nutrient absorption from the soil, and the potential for controlled release of agrochemicals, leading to enhanced productivity and environmental protection through precise application of nanopesticides and nanofertilizers [70]. Nanotechnology offers a sustainable approach to pest and disease management by enabling precise agrochemical delivery with minimal environmental impact. However, concerns like long-term safety, production costs, and regulatory gaps remain, though advancements in eco-friendly, biodegradable nanoparticles aim to overcome these challenges [71].

3.3. Remote Sensing and Artificial Intelligence (Ai) Tools: Use in Mapping And Managing Soil Degradation

Remote sensing integrated with Artificial Intelligence (AI) has been popping up as a vital tool for monitoring and addressing soil degradation, delivering accurate, timely, and cost-efficient insights. These technologies allow large-scale data collection and analysis, helping to detect degradation trends and support sustainable land management.

Land degradation is a significant global issue which renders land unsuitable for both human use and natural soil environment. Mitigating land degradation requires a deep understanding of its causes, effects, and severity. Effective monitoring of desertification has historically been limited by inefficient strategies. Land degradation is assessed through various means such as expert input, field surveys, user feedback, and modeling. Recent research increasingly emphasizes its value in accurately mapping land deterioration, degradation assessment, soil moisture studies, soil fertility, soil resource studies [72]. Remote sensing (RS) has significantly enhanced the availability of soil data, allowing for the generation of digital soil maps at fine resolutions. The utilization of diverse satellites has yielded significant covariate data for digital soil mapping (DSM) endeavors, enhancing the spatial management of soil characteristics over the last 20 years [73]. Various satellites, including Landsat, Sentinel, and MODIS, are extensively used for soil mapping. These platforms offer high-resolution data that are essential for digital soil mapping (DSM) and the assessment of soil resources [74].

GIS and RS are critical in assessing and managing soil degradation. Integrated with models like USLE (Universal Soil Loss Equation) and RUSLE (Revised Universal Soil Loss Equation), they allow precise estimation of soil loss—for instance, in Punjab's lower Sutlej River basin, soil loss ranged from 1.26 to 25 tonnes per hectare annually, with total loss exceeding 2.4 million tonnes. Studies in Ethiopia show an annual soil loss of 1.5 billion tonnes, with productive land potential declining by 2.2% per year in highland areas. These tools help delineate watersheds, identify erosion-prone zones, and prioritize sub-watersheds like WS8 (highest erosion) and WS2 (lowest erosion). RS also identified 80% of the Wonji sugarcane farm in Ethiopia as severely saline-affected. Despite their utility, challenges remain, including lack of access to technology, skilled personnel, and funding, Strengthening support for GIS and RS adoption is necessary for effective, data-driven soil conservation and sustainable land management [75].

Mapping and management of soil degradation through deep learning enhances the accuracy and efficiency over traditional methods. By leveraging advanced algorithms and high-resolution data, deep learning models can effectively identify, map, and predict various aspects of soil degradation, such as erosion, organic matter content, and overall soil health. This approach not only aids in understanding current soil conditions but also supports sustainable land management practices.

The challenges of land degradation in irrigated agro-ecosystems are addressed by RS and GIS tools that delineate, map and generate a holistic database on resources [76]. Efficiency and accuracy of soil health is monitored using special systems *viz*., Soil Health Intelligence System using Multispectral Imaging and Advanced Deep Learning Techniques (SHIDS-ADLT) by integrating multispectral imaging with advanced deep learning algorithms, allowing for precise identification of nutrient deficiencies, soil contamination, and other critical parameters affecting agricultural productivity. SHIDS-ADLT provides a scalable and user-friendly platform that facilitates real-time analysis and actionable recommendations for farmers, agronomists, and researchers, promoting sustainable agricultural practices and enabling prior detection of degradation of soils for timely management [77]. The mapping of peat land degradation at a 25cm resolution aided in identifying the drainage channels and erosion features, vital for carbon sink maintenance and estimation of GHG's emission through use of convolutional neural networks (CNNs) type of deep learning models [78]. Development of various conservation strategies utilizing high-resolution satellite images of deforestation activities like road construction, logging and natural disasters (forest fire) achieved through continuous monitoring can be helpful for mapping of forest degradation through deep learning models to obtain higher accuracy than traditional methods [79].

AI-driven perspectives of soil physiochemical properties such as moisture, pH, and nutrient levels yield accurate recommendations for fertigation, and soil management. When integrated with IoT and GIS, it improves resource efficiency, boosts agricultural yields, and promotes sustainable agriculture through fostering proactive decision-making and conservation of the environment [80]. A hybrid CNN-RF model using GeoAI and satellite imagery fusion accurately predicted soil texture (clay, sand, silt) with high precision. Using soil samples from Iran's Golestan province and data from Landsat-8, SRTM DEM, and weather parameters, the model outperformed standalone methods, offering improved tools for sustainable agriculture and soil management [81]. Reports from various studies introduced a deep learning approach to map soil degradation using 37 years of multi-temporal Landsat data, focusing on bare soil surfaces (BSS) instead of vegetation indices. Using 244 BSS masks, the model achieved 75% accuracy. The proposed Spectral Neighborhood of the Soil Line (SNSL) method analyzed RED and NIR bands to identify degradation, with ground validation showing strong correlation to organic matter and humus depth, confirming its effectiveness [82].

AI tools offer significant advancements in soil degradation management, but challenges remain in terms of data availability, model accuracy, and integration with existing agricultural practices. Additionally, the reliance on technology may pose accessibility issues for regions with limited resources. In spite of several setbacks in adopting AI, the continuous advancement and deployment of AI in soil conservation emphasize an affirmative response in eco-friendly management of soils.

4. Innovative Materials for Sustainable Soil Management

4.1. Carbon Sequestration and Nutrient Retention Using Biogenic Amendments

Globally climate change is emerging as a serious threat affecting the ecosystem. Mitigating the effects of climate change and boosting up the soil health by trapping the atmospheric carbon dioxide and storing it in the soil as biomass and retaining nutrients in the soil will help in holding of essential nutrients for plant growth. Resilient ecosystem and eco-friendly management of land are achieved through diversified agricultural and forestry practices.

Biochar, produced through pyrolysis, is known for its ability to alter the soil structure, nutrient holding, and carbon sequestration, while soil conditioners like crop residues and manure primarily impact the soil quality and microbial count. Both the products significantly impact soil health indicators, such as microbial biomass, nutrient availability, and greenhouse gas emissions.

Optimization of various soil health parameters, including soil pH, organic carbon content, cation exchange capacity, microbial biomass carbon, and reduced bulk density through biochar amendments by applying at higher rates (20 t ha^{-1} and 30 t ha^{-1}) resulted in increased strawberry yield and better fruit quality proving its effect on agronomic and economic benefits in organic agriculture Long-term carbon storage in soils [83].

Biochar enhances soil health by structural alteration, nutrient retention, and water-holding capacity, which supports better crop productivity. It also aids in carbon sequestration, helping mitigate climate change. Additionally, biochar shows promise in restoring degraded lands and remediating polluted soils. However, widespread use faces challenges like inconsistent properties from varied production methods, high costs, and the need for long-term research to assess its full impact [84].

Biochar, an anthropogenic material, significantly impacts the soil nitrogen (N) cycle, both directly and indirectly, thereby affecting soil ecological functions. Its unique properties play a pivotal role in soil amelioration and nutrient retention, which are integral to its effects on nitrogen dynamics. It influences the N cycle by adsorption of various nitrogen species, impacts various biochemical processes like nitrification, denitrification and nitrogen fixation. Biochar exhibits high surface area and porous structure, which enhances its ability to adsorb ammonium (NH_4^+) and nitrate (NO_3^-) which enhances the nitrogen retention and slow release and long-term availability of nutrients. The biochar affects the microbial community based on pH and moisture levels as well as lowers the bulk density promoting aeration [85]. Application of biochar along with different nitrogen sources enhances the soil health and supports sustainable agricultural practices thereby impacting the crop yield and environment. The effects of biochar and biodegradable nitrogen on alkaline soils in semi-arid regions, finding that combining biochar at 30 t ha^{-1} with nitrogen at 150 kg ha^{-1} from poultry manure or FYM significantly enhances soil fertility and carbon sequestration [86]. Biochar amendments can lead to significant increases in SOC stocks, although the stability of these stocks varies depending on soil texture and biochar properties [87].

Organic amendments significantly increase SOC content, with studies showing an average increase of 26.9% in SOC due to amendment application. This increase is attributed to the addition of organic matter, which enhances carbon storage in soils [88].

Biochar, along with organic amendments like rice husk, coconut coir, and sheep manure, enhances carbon sequestration and improves nutrient cycling by influencing microbial activity in soils. These amendments reduce carbon limitation and increase nitrogen demand, boosting soil fertility. Their effectiveness varies with soil texture. Biochar and rice husk perform better in clayey soils by enhancing enzyme activities linked to carbon, nitrogen, and phosphorus, while in sandy soils, sheep manure supports carbon and phosphorus cycling, and biochar aids nitrogen-related enzymes [89]. It provides a stable form of carbon that resists decomposition, thus contributing to long-term carbon storage. The application of organic amendments in cropping systems, such as wheat-maize, has been shown to increase crop carbon uptake and reduce carbon dioxide emissions, further contributing to carbon sequestration [90].

4.2. Compost, Vermicompost, and Green Manures: Enhancing Microbial Life and Nutrient Cycling

The soil health preservation is a basic element of eco-friendly agriculture practice through increased microbial population. Soil microorganisms, encompassing bacteria, fungi, and archaea, are indispensable to the processes of nutrient cycling, organic matter decomposition, and disease control, all of which significantly enhance soil fertility and promote plant growth. Diversified microbes are shaped by a multitude of natural and anthropogenic determinants, their interactions with soil characteristics and plant roots are critical for the sustenance of robust soil ecosystems.

Sustainable methodologies such as composting, crop rotation, and the application of organic amendments significantly augment this biodiversity. Assessing soil health indicators can guide tailored strategies to maintain productivity [91]. Both conventional composting methods and vermicomposting approaches markedly improved the concentrations of SOC, total phosphorus, and the availability of phosphorus, while concurrently augmenting the enzymatic activities of soil enzymes pertinent to the cycling of carbon and phosphorus, including α-glucosidase, β-glucosidase, acid phosphomonoesterase, and alkaline phosphomonoesterase [92]. Vermicomposting effectively converts large amounts of organic waste into high-quality organic fertilizer, resulting in a nutritionally rich and biologically active product that enhances soil health and supports sustainable nutrient management in agricultural soils. It emphasizes that the use of vermicomposting not only improves crop growth and yield but also contributes to reducing environmental pollution by efficiently managing waste materials [93].

Vermicomposting improves soil fertility and crop growth by enriching beneficial microbes, enhancing plant hormones and enzymes, and increasing resistance to pests and diseases. Its high nutrient content, water retention, and permeability make it valuable for sustainable agriculture and eco-friendly waste management across various sectors [94]. The carbon is sequestered by recycling organic waste into nutrient enriched soil amendment which reduces the GHGs emission. The use of vermicompost improves soil health and increases yields by enhancing soil makeup and biochemical properties, leading to higher nutrient density in plants and overall better agricultural productivity [95].

4.3. Zeolites, Hydrogels, and Polymers: Soil Moisture Regulation and Nutrient Holding Capacity

Zeolites, hydrogels, and polymers are progressively acknowledged for their potential to augment soil moisture regulation and enhance nutrient retention capacity, both of which are essential for eco-friendly agriculture. These materials possess distinctive characteristics that can optimize water use efficiency (WUE) and nutrient use efficiency (NUE), consequently facilitating plant development while diminishing ecological repercussions. The utilization of zeolites functions as soil ameliorants (**Figure 5**).

Zeolites are increasingly acknowledged for their function as effective soil conditioners, proficient in enhancing both the physicochemical properties of soil. Their integration into agronomic systems has been demonstrated to augment permeability, saturated hydraulic conductivity, water retention capacity, and cation exchange capacity. These attributes contribute to more sustainable agricultural practices by increasing water use efficiency (WUE) and nutrient use efficiency (NUE). Zeolites accomplish this by sequestering water and critical nutrients such as ammonium, nitrate, phosphate, potassium, and sulfate within their porous matrix, thereby elevating crop yields and mitigating the potential for nutrient leaching into surface and groundwater [96]. Integrating superabsorbent polymer hydrogels with soil conservation practices enhances crop productivity by conserving water and nutrients and protecting seeds from stress. Biodegradable polysaccharide hydrogels offer a sustainable alternative to synthetic ones, serving as soil conditioners, fertilizer carriers, and slow-release pesticide systems, while reducing environmental impact [97]. Hydrogels embedded with municipal sludge-derived hydrochar have shown improved water retention, nutrient release, and plant growth support, making them promising for sustainable agriculture in arid regions [98]. Potassium polyacrylate-derived hydrogels markedly enhance the moisture retention capabilities of sandy soils, thereby presenting a viable approach for the conservation of water in arid and semi-arid agricultural zones[99]. Synthetic amendments have a more pronounced impact on soil health compared to organic amendments. The comparative effects of organic versus synthetic amendments on soil health are detailed in **Table 2.**

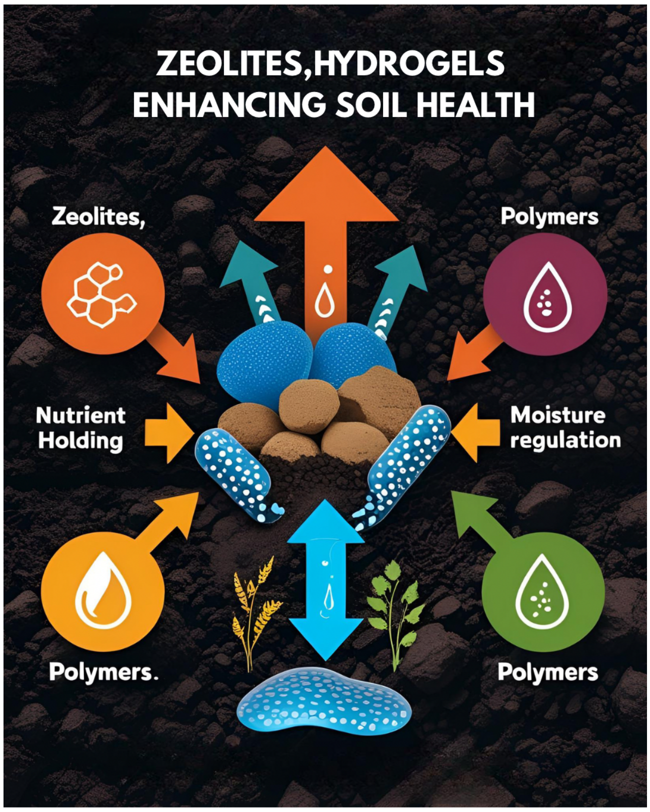

Figure 5. Zeolites, Hydrogels, and Polymers.

Table 2. Comparative Effect of Organic vs Synthetic Amendments on Soil.

Soil Property	Organic Amendments	Synthetic Amendments	Source
Soil Structure & Aggregation	Improve aggregation due to higher organic matter input and microbial activity	Often degrade structure over time due to lack of organic matter	Naushabayev et al.[100]; Lal,[101]
Water Retention	Increases water-holding capacity by enhancing soil porosity and humus content	Minimal impact; may even reduce porosity with long-term use	Chivenge et al.[102]
pH Stability	Buffers pH due to organic acids and complexation	May acidify soils over time, especially with ammonium-based fertilizers	Bhattacharyya et al.[103] Edmeades,[104]
Cation Exchange Capacity (CEC)	Enhances CEC by contributing humic substances	No contribution; can reduce CEC indirectly through soil acidification	Lorenz & Lal[105]
Nutrient Release	Slow, sustained release; aligns with microbial and plant uptake	Rapid nutrient availability; risk of leaching and runoff	Leifeld & Fuhrer[106]
Soil Organic Carbon (SOC)	Substantially increases SOC stocks and promotes carbon sequestration	Typically reduces SOC over time if not combined with organic sources	Diacono & Montemurro[107]; Naushabayev et al.[100]
Microbial Biomass	Stimulates microbial growth, diversity, and enzymatic activity	Often suppresses microbial diversity, especially with high doses	Lehmann et al.[108]
Soil Enzymatic Activity	Increases due to carbon input and microbial stimulation	May decline under heavy or prolonged synthetic use	Maeder et al.[109]
Long-Term Soil Health	Enhances long-term resilience, fertility, and ecological balance	May lead to nutrition deficiency, compaction, and degradation	Ding et al.[110]

5. Soil Health and Climate Change

Climate change exerts a substantial influence on soil processes through modifications in temperature, precipitation patterns, and biological activity, thereby impacting SOC concentrations, microbial diversity, and the structural integrity of the soil. Elevated temperatures enhance the rate of organic matter decomposition, which results in a decline in SOC and microbial diversity. Catastrophic climatic events, including floods and droughts, further disrupt soil structure, exacerbate erosion, and diminish the availability of essential nutrients that alter the soil quality and ecosystem functioning.

Elevated temperatures attributable to climate change expedite the process of SOM decomposition, consequently resulting in diminished stocks of SOC. This phenomenon is predominantly due to the fact that the rate of SOM decomposition exhibits a pronounced sensitivity to variations in temperature, which may surpass the rate at which carbon is introduced through plant detritus and organic material, ultimately culminating in a net loss of carbon from soil systems [111]. The fluctuation in temperature shows a significant impact on the microbial community by affecting their physiological characteristics, symbiotic relations with plants that impacts the recycling of nutrients and maintenance of soil health [112].

Soil formation process is affected by variable patterns of precipitation such as droughts and floods. Drought implies reduced soil moisture which limits microbial activities and nutrient availability and floods may cause soil erosion and loss of nutrients by leaching.

Changes in precipitation patterns, including increased frequency of droughts and floods, significantly impact soil processes. Drought conditions reduce soil moisture, which can limit microbial activity and nutrient availability, whereas soil erosion and nutrient leaching occur due to floods [113].

Reduced rainfalls have demonstrated the suppression of soil multifunctionality in semiarid regions, an aspect that has lowered the nutrient provisioning and the efficiency of the microbial growth. In contrast, the precipitation can stimulate the efficiency of microbial growth improvement, however, it does not influence the global multifunctionality of soil significantly [114]. Fertile soils are subjected to erosion and structural degradation due to extreme weather conditions *viz*., heavy rainfall, storms therefore contributing to loss of SOC and increased mineralization [111,115].

Reports on adverse impacts of climate change, the adverse impacts of climate change on soil processes are reported but on the other side the potential adaptive tactics for eco-friendly land management practices like common agronomic practices *viz.,* no-tillage, crop rotation and organic amendments which improve soil quality by fostering microbial growth and soil structure, also SOC sequestration [116].

5.1. Soil as a Carbon Sink: Mitigation Strategies

The capturing of atmospheric CO_2 and storing it as biomass in soil helps in reducing the GHGs emission and acts as a natural carbon sink. The capturing ability is influenced by factors, including soil management practices, land use, and climate conditions. There are good soil management practices that can help increase soil organic carbon (SOC), hence through that climate change will be addressed. The solution to this question will examine the importance of soil as a carbon sink and measures that can be undertaken to strengthen carbon sequestration abilities of the soil (**Figure 6**).

Carbon Storage Capacity: Soil is the largest terrestrial carbon sink, holding around three times as much carbon as in the atmosphere and holding four and a half times as much carbon as in the biotic pool. Because of this, soil is a key player in the global carbon cycle and a possible controller of greenhouse gases as CO_2, N_2O and CH_4 [117,118].

5.2. Technological Adaptation Across Agro-Ecological Zones

In the context of climate change, to enhance the agricultural productivity and resilience, technological adaptation across the various agro-ecological regions is highly recommended. Technological adaptations include agro-forestry, climate-smart agriculture and conservation agriculture which are localized due to heterogenetic nature of these zones to maximize the efficacy. For instance, in Ethiopia, the implementation of carbon farming and CSA methodologies has been demonstrated to augment resilience and mitigate emissions when tailored to regional conditions [119]. The improved soil fertility in the semi-arid regions of Tanzania is reported due to conservative agricultural practices which efficiently use the resources. This discourse will examine the adaptation of these technologies across various agro-ecological zones, concentrating on their execution and resultant impacts[120].

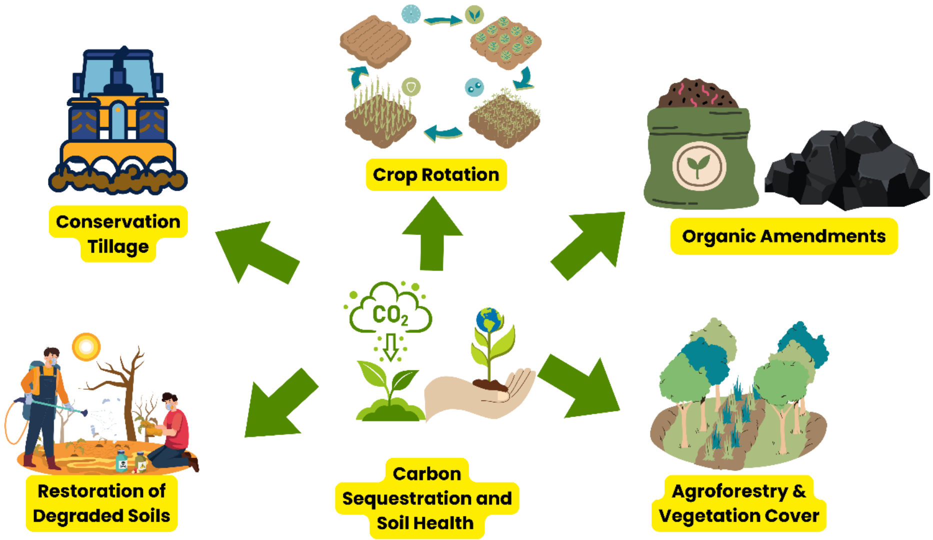

Figure 6. Soil as a Carbon Sink: Mitigation Strategies.

In agroforestry, trees are paired up with crops and animals and help to increase biodiversity and carbon sequestration. In Ethiopia, carbon farming includes use of agroforestry system that enhances storage of carbon in soil and improves soil health which supports climate change mitigation and ecosystem resilience. Carbon farming also known as earth-friendly farming is a significant way to trap CO_2 and hold it in the ground and plants. This technology not only cuts down the amount of greenhouse gases discharged but also helps in raising the level of soil fertility and the capacity to hold water as well[119].

5.2.1. Climate-Smart Agriculture (CSA)

The enhancement of agricultural output is achieved by practicing CSA as it is a holistic approach of production, mitigation and adaptation goals that include the reduction of GHGs emissions, diversified cropping patterns and maximizing resource-use efficiency. The CSA practices are impacted by climate information authorization, training and extension services which are essential for ensuring food security[121,122].

5.2.2. Conservation Agriculture

Farming practices like minimum tillage, residue management and crop rotation are the vitals of the Conservation agriculture (CA) concept which improve the soil health by increasing moisture conservation, and increase nutrient buildup, leading to higher crop productivity. In the context of Ethiopia, Conservation Agriculture (CA) has been recognized as a pivotal approach for both climate change adaptation and mitigation, facilitating enhancements in soil organic carbon sequestration while simultaneously decreasing greenhouse gas emissions[123,124]. The adoption of different soil management strategies influences various soil properties. The comparative impacts of these strategies on soil health are presented in **Table 3.**

5.2.3. Adaptation Strategies Across Agro-Ecological Zones

Different agro-ecological regions are subject to choosing various farm types and adaptive strategies for CA. For example, Africa being a drought prone or dry land continent the strategies are adopted based on its crop and climatic conditions. In semi-arid regions, the implementation of conservation agriculture has demonstrated efficacy in the enhancement of soil fertility, whereas in elevated terrains, livestock management practices are customized to align with the distinct climatic conditions.

Although the incorporation of technological innovations is a most significant trigger of agricultural resiliency, one should consider the socio-economic processes that impose an impact on the process of adoption of such procedures.

Factors which influence the outcome of adaptation strategies are the ease of access to resources, education levels, and the status of social equity. Moreover, the possibility of the maladaptation emerges in case the interventions fail to take into consideration the underlying socio-economic systems that make some farmers more vulnerable to the negative effects of the climate change. The need is therefore a more transformational structure which is able to address these structural factors leading to establishing a state of vulnerability towards achieving sustainable development goals [124].

Table 3. Comparative Impact of Soil Management Strategies on Soil Health.

Management Strategy	Physical Impact	Chemical Impact	Biological Impact	SOC Impact	Source
Conservation Tillage	Enhances aggregation, reduces erosion, improves bulk density	Improves nutrient stratification, slows acidification	Promotes microbial biomass in upper layers	Slows SOC loss; promotes sequestration in surface soil	Hellin et al. [125]
Cover Cropping	Improves structure and water infiltration; reduces compaction	Enhances nutrient availability, especially N and P	Increases microbial diversity and enzymatic activity	Builds SOC by continuous organic input	Franzluebbers. [126]
Crop Rotation	Breaks up hardpans; improves porosity and texture	Enhances nutrient cycling; mitigates nutrient mining	Diversifies microbial communities; enhances symbiotic interactions	Moderate increase in SOC, especially in diversified systems	Sisay et al. [122]
Organic Farming	Improves soil porosity and aggregate stability	Increases CEC, pH buffering, and macro-nutrient availability	Substantial rise in microbial activity, earthworm biomass, and enzymatic diversity	Strong enhancement of SOC due to regular organic input	Lehmann et al. [108]; Lorenz & Lal [105]
Integrated Nutrient Mgmt.	Maintains structure by combining organic/inorganic inputs	Reduces risk of nutrient leaching; balances short and long-term nutrient availability	Promotes beneficial soil fauna and microbial metabolism	Sustains or improves SOC, depending on organic input levels	Lal, [101]
No-Till + Organic Inputs	Maximum improvement in physical parameters like infiltration and aggregation	Sustained nutrient availability with reduced synthetic input	Very high microbial biomass and activity	Long-term SOC buildup and enhanced carbon stabilization	Naushabayev et al. [100] ; Poeplau et al. [127]
Conventional Tillage	Leads to compaction, soil crusting, and erosion	Often causes pH shifts and nutrient loss due to leaching	Disrupts microbial networks; reduces biodiversity	Accelerates SOC depletion	Gattinger et al. [128]

6. Challenges and Gaps in Current Research

The absence of prescribed protocols for evaluation across stratified agro-ecosystems is the major limitation. The non-uniformity hinders consistent tracking and comparison of indicators of soil health between regions and globally thus compromising the efficacy of soil management interventions. Moreover, due to less access and availability of laboratory facilities in most regions, it is difficult to carry out in-depth diagnostics of the soil health and thereby hindering the process of creating efficient and site-specific approaches to remediation of the soil.

Predictive assessments of soil health based solely on land use or management practices are often unreliable due to the dynamic nature of soil physico-chemical, and biological interactions. These processes vary across spatial and temporal scales, making it difficult to evaluate watershed health or the long-term effectiveness of conservation strategies. Further complicating this is the influence of legacy land-use practices, climatic variability, and the inherently slow turnover rates of soil systems, all of which obscure direct correlations between soil health and water quality. Current remediation technologies whether physical, chemical, or biological struggle to maintain soil integrity while addressing contamination. The persistence of pollutants in soil, coupled with the high cost and complexity of remediation, underscores the urgent need for preventive strategies focused on minimizing soil pollution at the source.

Remote sensing and smart sensor systems are novel technological inputs used in monitoring the soil health. On the other hand, the adoption of these technologies has multiple barriers such as being highly economical. technical limitations, lack of integration with traditional farming practices, and the need for specialized skills to operate and interpret the data. In remote sensing applications, particularly for soil salinity assessment, there is a significant trade-off between spatial coverage, resolution, and data accuracy. Most sensors offer limited spatial and temporal resolution, restricting salinity studies to localized areas and making long-term monitoring difficult. The scarcity of reliable ground data further limits validation, owing to the heterogeneous nature of soil properties, inconsistent sampling methodologies, and limited accessibility of some field locations.

The crucial challenge in modern agriculture is efficient application of nutrients to the crop. Environmental issues linked to the overuse or disproportionate application of fertilizers underscore the necessity for integrated nutrient management (INM) approaches that amalgamate organic, inorganic, and biological inputs. INM presents significant potential for bolstering soil fertility and promoting sustainability while enhancing adaptive capacity in the context of climate change; however, its broad adoption is still constrained by a deficiency in awareness, education, and conducive policy frameworks.

7. Future Prospects and Recommendations: Multidisciplinary Approach Integrating Tech, Policy, and Farmer Education

A globally adaptable soil health assessment (SHA) methodology is urgently required to serve farmers from various socio-economic backgrounds and agroecological zones. Contemporary assessment instruments frequently depend on complex and expensive laboratory techniques, constraining their feasibility and broad use, particularly in resource-limited environments. Establishing location-specific indicator baselines and threshold values is essential, as the generalized use of global references fails to reflect the inherent variability in soil-climate interactions. This underscores the imperative for the formulation of assessment frameworks that are specifically customized to regional contexts, ensuring alignment with prevailing environmental conditions. Moreover, an extensive comprehension of the interrelationships between soil vitality and ecological preservation is essential.

The future investigations focused on determining specific soil characteristics that facilitate sustainable land management strategies, employing interdisciplinary frameworks that harmonize ecological sustainability with socio-economic requirements. Conservation of soil health along with water and air quality is coordinated with resource management and assessment of long-term ecological ramifications, while the sustainability of nanomaterial applications in soil remediation and land rehabilitation also demands comprehensive scrutiny. The interactions between the nanomaterials and soil microbiota are understudied and the impact on the environment is less known. Furthermore, forthcoming research endeavors should encompass longitudinal field studies aimed at evaluating the cumulative impacts of diverse soil management strategies on soil quality, agricultural yield, and ecosystem functionalities over extended periods.

Ultimately, there exists an increasing imperative to integrate participatory research strategies that involve farmers as integral participants in the research framework. Engaging local knowledge and the experiential insights of farmers can yield more contextually relevant and pragmatic solutions that effectively tackle the real-world challenges encountered by agricultural communities across various regions.

Future investigations ought to emphasize a comprehensive examination of the functional dynamics of microbial communities in nutrient cycling, particularly within the context of tropical agroecosystems. It is imperative to comprehend the influence of agricultural methodologies such as crop rotation, the application of organic amendments, and INM on microbial diversity and ecological functions, as this knowledge is crucial for the enhancement of soil health and agricultural productivity. The advancement of our capabilities to monitor and analyze microbial structure and diversity is of paramount importance; consequently, the establishment of standardized and rigorous methodologies for the evaluation of microbial indicators in relation to soil attributes represents a significant research imperative. Furthermore, the expansion of research concerning the long-term ramifications of organic waste management practices, especially vermicomposting and traditional composting, is essential. These investigations should concentrate on assessing alterations in soil characteristics, nutrient retention, and crop yield across diverse agro-climatic zones and cropping systems. Analyzing the specific responses of bacterial and fungal populations to various organic inputs will also yield valuable insights into enhancing nutrient cycling and promoting soil resilience.

8. Conclusion

Soil quality serves as the cornerstone of sustainable agriculture, ecosystem functionality, and food security. This review has underscored the multifaceted nature of soil health, encompassing physical, chemical, and biological attributes, and the challenges associated with their standardized assessment across diverse agroecological zones. While substantial progress has been made in understanding soil-microbe interactions, nutrient cycling, and the benefits of organic amendments such as vermicompost, key gaps persist, particularly in long-term impact studies and microbial functionality under varied environmental conditions. Technological innovations such as remote sensing and sensor-based monitoring present promising avenues for non-invasive soil assessment. However, limitations in spatial resolution, data validation, and integration with field-level practices constrain their widespread adoption. Additionally, existing remediation strategies face significant challenges in balancing effectiveness with the preservation of soil structure and ecological balance. To ensure holistic soil management, future efforts must focus on developing accessible, low-cost, and locally adaptable assessment frameworks, fostering farmer participation, and promoting interdisciplinary research that integrates agronomic, ecological, and socio-economic dimensions. Addressing these deficiencies will not only facilitate the progression of scientific knowledge but also promote the execution of contextually relevant strategies that improve productivity, foster environmental sustainability, and bolster resilience against climatic fluctuations. Ultimately, a cohesive and inclusive methodology towards soil health will be crucial in satisfying the worldwide requirement for sustainable land utilization and food generation. Recent advances in technology, including precision agriculture tools, remote sensing, artificial intelligence, and nanotechnology, offer powerful means to monitor, manage, and improve soil conditions in real time. These advanced technologies facilitate interventions tailored to specific sites, thereby enhancing the efficient utilization of resources and mitigating detrimental environmental consequences. Cutting-edge materials, including biochar, nano-fertilizers, and organic amendments, play a pivotal role in the sustainable management of soil by augmenting nutrient availability, enhancing soil structure, and fostering microbial activity. Their incorporation into established agricultural practices aids in carbon sequestration and alleviates the negative impacts associated with intensive agricultural methodologies. Furthermore, the health of soil is instrumental in both the mitigation and adaptation strategies related to climate change. Well-maintained soils function as carbon sinks, regulate hydrological cycles, and provide resilience against climatic extremes, emphasizing the imperative for climate-smart soil management methodologies. As global challenges escalate, a synergistic paradigm that amalgamates traditional knowledge with contemporary innovations is vital for the enhancement of soil health, the assurance of food security, and the preservation of environmental integrity.

Authors Contribution

Conceived and designed the review, carried out the concept, R.S., P.K.B., and A.P.; Prepared the figure KV., B.J.K., and V.K.;. All the authors equally contributed to the entire writing. Provided guidance on the whole concept and improved the manuscript, H.S.J.; Authors read and approved the final version of the manuscript, L.T.L., A.P.S., P.K.B., H.S.J.; All the authors given consent to submit the manuscript.

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Conflicts of Interest

The authors declare they do not have any conflict of interest.

References

[1] Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology. 15(1), 3–11. DOI: https://doi.org/10.1016/S0929-1393(00)00067-6

[2] Bhaduri, D., Sihi, D., Bhowmik, A., et al., 2022. A review on effective soil health bio-indicators for ecosystem restoration and sustainability. Frontiers in Microbiology. 13, 938481. DOI: https://doi.org/10.3389/fmicb.2022.938481

[3] Usharani, K.V., Roopashree, K.M., Naik, D., 2019. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. Journal of Pharmacognosy and Phytochemistry. 8(5), 1256–1267. Available from: https://www.phytojournal.com/archives/2019.v8.i5.9750/role-of-soil-physical-chemical-and-biological-properties-for-soil-health-improvement-and-sustainable-agriculture (cited 2 August 2025).

[4] Powlson, D.S., 2021. Is 'soil health' meaningful as a scientific concept or as terminology? Soil Use and Management. 37(3), 403–405. DOI: https://doi.org/10.1111/sum.12721

[5] Baveye, P.C., 2021. Soil health at a crossroad. Soil Use and Management. 37(2), 215–219. DOI: https://doi.org/10.1111/sum.12703

[6] Lal, R., 2020. Managing soils for resolving the conflict between agriculture and nature: The hard talk. European Journal of Soil Science. 71(1), 1–9. DOI: https://doi.org/10.1111/ejss.12857

[7] United Nations, 2024. Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture. Available from: https://sdgs.un.org/goals/goal2 (cited 2 August 2025).

[8] Silveira, M.L.A., 2005. Dissolved organic carbon and bioavailability of N and P as indicators of soil quality. Scientia Agricola. 62(5), 502–508. DOI: https://doi.org/10.1590/S0103-90162005000500017

[9] Mankotia, R., Sharma, R., Sepehya, S., et al., 2019. Soil Health Assessment and Its Sustenance. International Journal of Current Microbiology and Applied Sciences. 8(08), 1978–1987. DOI: https://doi.org/10.20546/ijcmas.2019.808.231

[10] Srivastava, P., Balhara, M., Giri, B., 2020. Soil Health in India: Past History and Future Perspective. In: Giri, B., Varma, A. (eds.). Soil Health, Soil Biology. Springer International Publishing, Cham: Switzerland. pp. 1–19. DOI: https://doi.org/10.1007/978-3-030-44364-1_1

[11] Meena, R.S., Kumar, S., Rao, C.S., et al., 2022. Reforming the Soil Organic Carbon Management Plans and Policies in India. In: Meena, R.S., Rao, C.S., Kumar, A. (eds.). Plans and Policies for Soil Organic Carbon Management in Agriculture. Springer Nature Singapore: Singapore. pp. 1–25. DOI: https://doi.org/10.1007/978-981-19-6179-3_1

[12] Guo, M., 2021. Soil Health Assessment and Management: Recent Development in Science and Practices. Soil Systems. 5(4), 61. DOI: https://doi.org/10.3390/soilsystems5040061

[13] Cardoso, E.J.B.N., Vasconcellos, R.L.F., Bini, D., et al., 2013. Soil health: looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? Scientia Agricola. 70(4), 274–289. DOI: https://doi.org/10.1590/S0103-90162013000400009

[14] Chahal, I., Saurette, D.D., Van Eerd, L.L., 2023. Soil texture influences on soil health scoring functions in Ontario agricultural soils: a possible framework towards a provincial soil health test. Canadian Journal of Soil Science. 103(1), 152–163. DOI: https://doi.org/10.1139/cjss-2021-0145

[15] Karlen, D.L., Stott, D.E., 2015. A Framework for Evaluating Physical and Chemical Indicators of Soil Quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., et al. (eds.). Defining Soil Quality for a Sustainable Environment, SSSA Special Publications. Soil Science Society of America and American Society of Agronomy: Madison, WI, USA. pp. 53–72. DOI: https://doi.org/10.2136/sssaspecpub35.c4

[16] Kibblewhite, M.G., Ritz, K., Swift, M.J., 2008. Soil health in agricultural systems. Philosophical Transactions of the Royal Society B: Biological Sciences. 363(1492), 685–701. DOI: https://doi.org/10.1098/rstb.2007.2178

[17] Allen, D.E., Singh, B.P., Dalal, R.C., 2011. Soil Health Indicators Under Climate Change: A Review of Current Knowledge. In: Singh, B.P., Cowie, A.L., Chan, K.Y. (eds.). Soil Health and Climate Change, Soil Biology. Springer: Berlin, German. pp. 25–45. DOI: https://doi.org/10.1007/978-3-642-20256-8_2

[18] Pankhurst, C., Hawke, B., McDonald, H., et al., 1995. Evaluation of soil biological properties as potential bioindicators of soil health. Australian Journal of Experimental Agriculture. 35(7), 1015–1028. DOI: https://doi.org/10.1071/EA9951015

[19] Alkorta, I., Aizpurua, A., Riga, P., et al., 2003. Soil Enzyme Activities as Biological Indicators of Soil Health. Reviews on Environmental Health. 18(1), 65–73. DOI: https://doi.org/10.1515/REVEH.2003.18.1.65

[20] Paltseva, A., 2024. What Is Soil Texture?. In: The Urban Soil Guide: A Field and Lab Manual. Springer Nature: Cham, Switzerland. pp. 25–30. DOI: https://doi.org/10.1007/978-3-031-50777-9_4

[21] Li, Y., Wang, H., Zhao, J., et al., 2015. Effects of tillage methods on soil physicochemical properties and biological characteristics in farmland: A review. Journal of Applied Ecology. 26(3), 939–948. Available from: https://pubmed.ncbi.nlm.nih.gov/26211079/ (cited 2 August 2025).

[22] Zhang, C., Li, W., 2008. Regional-scale modelling of the spatial distribution of surface and subsurface textural classes in alluvial soils using Markov chain geostatistics. Soil Use and Management. 24(3), 263–272. DOI: https://doi.org/10.1111/j.1475-2743.2008.00165.x

[23] Mohammed, S.B., Karaca, U.Ç., Al-Solaimani, S.G., 2024. Exploring the Physical, Chemical, and Biological Properties of Soils from Different Regions Classified into Different Textural Classes, 2024 . Open Access Journal of Applied Science and Technology. 2(1), 01–07. DOI: https://doi.org/10.33140/OAJAST.02.01.05

[24] Abishek, J., Kannan, P., Devi, M.N., et al., 2023. Soil Texture Prediction Using Machine Learning Approach for Sustainable Soil Health Management. International Journal of Plant & Soil Science. 35(19), 1416–1426. DOI: https://doi.org/10.9734/ijpss/2023/v35i193685

[25] Zega, N.D., 2024. The Influence of Soil Texture and Structure on the Distribution of Water and Air in the Soil Profile. Jurnal Ilmu Pertanian dan Perikanan. 1(2), 1–6. DOI: https://doi.org/10.70134/penarik.v1i2.52 (in Indonesian)

[26] Dewangan, S.K., 2023. Using the Soil Texture Triangle to Evaluate the Effect of Soil Texture on Water Flow: A Review. International Journal for Research in Applied Science and Engineering Technology. 11(6), 389–393. DOI: https://doi.org/10.22214/ijraset.2023.53635

[27] Franzluebbers, A.J., 2025. Sand is the unifying textural component influencing surface-soil carbon and nitrogen fractions across undisturbed land uses in North Carolina. Soil Science Society of America Journal. 89(1), e70011. DOI: https://doi.org/10.1002/saj2.70011

[28] Kaur, J., Singh, G., Shubham, ., et al., 2024. Harmonizing Agriculture: Nurturing Soil through Micronutrients Management and Texture Dynamics. International Journal of Plant & Soil Science. 36(6), 188–199. DOI: https://doi.org/10.9734/ijpss/2024/v36i64621

[29] Kimmell, L.B., Fagan, J.M., Havrilla, C.A., 2023. Soil restoration increases soil health across global drylands: A meta-analysis. Journal of Applied Ecology. 60(9), 1939–1951. DOI: https://doi.org/10.1111/1365-2664.14459

[30] Bodner, G., Zeiser, A., Keiblinger, K., et al., 2023. Managing the pore system: Regenerating the functional pore spaces of natural soils by soil-health oriented farming systems. Soil and Tillage Research. 234, 105862. DOI: https://doi.org/10.1016/j.still.2023.105862

[31] Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil and Tillage Research. 79(2), 131–143. DOI: https://doi.org/10.1016/j.still.2004.07.002

[32] Sun, Z., Arthur, E., De Jonge, L.W., et al., 2015. Pore Structure Characteristics After 2 Years of Biochar Application to a Sandy Loam Field. Soil Science. 180(2), 41–46. DOI: https://doi.org/10.1097/SS.0000000000000111

[33] Ghosh, T., Maity, P.P., Das, T.K., et al., 2020. Variation of porosity, pore size distribution and soil physical properties under conservation agriculture. The Indian Journal of Agricultural Sciences. 90(11), 2051–2058. DOI: https://doi.org/10.56093/ijas.v90i11.108558

[34] Goyal, D., Joshi, V., Gupta, N., et al., 2022. Soil Quality Assessment in a Landslide Chronosequence of Indian Himalayan Region. Land. 11(10), 1819. DOI: https://doi.org/10.3390/land11101819

[35] Morya, R., Bhargava, A., Lalitha, G.R., et al., 2023. Soil Management Practices to Enhance Carbon Sequestration Rates—A Review. International Journal of Environment and Climate Change. 13(11), 3762–3776. DOI: https://doi.org/10.9734/ijecc/2023/v13i113556

[36] Meena, R.S., Singh, A.K., Jatav, S.S., et al., 2024. Significance of soil organic carbon for regenerative agriculture and ecosystem services. In: Biodiversity and Bioeconomy. Elsevier: Frisco, TX, USA. pp. 217–240. DOI: https://doi.org/10.1016/B978-0-323-95482-2.00010-9

[37] Bajgai, Y., Kristiansen, P., Hulugalle, N., et al., 2014. Factors and Mechanisms Regulating Soil Organic Carbon in Agricultural Systems. In: Benkeblia, N. (ed.). Agroecology, Ecosystems, and Sustainability, Advances in Agroecology. CRC Press: Boca Raton, FL, USA. pp. 41–56. DOI: https://doi.org/10.1201/b17775-3

[38] Farooqi, Z.U.R., Hussain, M.M., Qadeer, A., et al., 2021. Role of carbon cycle in soil productivity and carbon fluxes under changing climate, in: Frontiers in Plant-Soil Interaction. Elsevier: Frisco, TX, USA. pp. 29–48. DOI: https://doi.org/10.1016/B978-0-323-90943-3.00017-1

[39] Gaiser, T., Stahr, K., 2013. Soil Organic Carbon, Soil

Formation and Soil Fertility. In: Lal, R., Lorenz, K., Hüttl, R.F., et al. (eds.). Ecosystem Services and Carbon Sequestration in the Biosphere. Springer: Dordrecht, Netherlands. pp. 407–418. DOI: https://doi.org/10.1007/978-94-007-6455-2_17

[40] Masciandaro, G., Macci, C., Peruzzi, E., et al., 2018. Soil Carbon in the World: Ecosystem Services Linked to Soil Carbon in Forest and Agricultural Soils, in: The Future of Soil Carbon. Elsevier: Frisco, TX, USA. pp. 1–38. DOI: https://doi.org/10.1016/B978-0-12-811687-6.00001-8

[41] Wiesmeier, M., Urbanski, L., Hobley, E., et al., 2019. Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales. Geoderma. 333, 149–162. DOI: https://doi.org/10.1016/j.geoderma.2018.07.026

[42] Lal, R., 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology. 24(8), 3285–3301. DOI: https://doi.org/10.1111/gcb.14054

[43] Yang, H., Prelovsek, M., Huang, F., et al., 2019. Quantification and evaluation of soil organic carbon and its fractions: case study from the Classical Karst, SW Slovenia. Acta Carsologica. 48(3). DOI: https://doi.org/10.3986/ac.v48i3.7305

[44] Sharma, S., Lishika, B., Shubham, et al., 2023. Soil Quality Indicators: A Comprehensive Review. International Journal of Plant & Soil Science. 35(22), 315–325. DOI: https://doi.org/10.9734/ijpss/2023/v35i224139

[45] Barrow, N.J., Hartemink, A.E., 2023. The effects of pH on nutrient availability depend on both soils and plants. Plant and Soil. 487(1–2), 21–37. DOI: https://doi.org/10.1007/s11104-023-05960-5

[46] Radulov, I., Berbecea, A., 2024. Nutrient Management for Sustainable Soil Fertility. In: Singh Meena, V., Swaroop Bana, R., Kishor Fagodiya, R., et al. (eds.), Agricultural Sciences. IntechOpen: London, UK. DOI: https://doi.org/10.5772/intechopen.1006692

[47] Yoni, M., 2024. The Role of Sudanese Forests Agroecosystem in Improving the Cation Exchange Capacity and Exchangeable Bases of a Sandy Soil in Western Burkina Faso. International Journal of Plant & Soil Science. 36(12), 189–207. DOI: https://doi.org/10.9734/ijpss/2024/v36i125194

[48] Pandao, M.R., Thakare, A.A., Choudhari, R.J., et al., 2024. Soil Health and Nutrient Management. International Journal of Plant & Soil Science. 36(5), 873–883. DOI: https://doi.org/10.9734/ijpss/2024/v36i54583

[49] Zhang, H., Jiang, N., Zhang, S., et al., 2024. Soil bacterial community composition is altered more by soil nutrient availability than pH following long-term nutrient addition in a temperate steppe. Frontiers in Microbiology. 15, 1455891. DOI: https://doi.org/10.3389/fmicb.2024.1455891

[50] Pagliaccia, D., Ortiz, M., Rodriguez, M.V., et al., 2024. Enhancing soil health and nutrient availability for Carrizo citrange (X Citroncirus sp.) through bokashi and biochar amendments: An exploration into indoor sustainable soil ecosystem management. Scientia Horticulturae. 326, 112661. DOI: https://doi.org/10.1016/j.scienta.2023.112661

[51] Kumar, D., Purakayastha, T.J., Das, R., et al., 2022. Long-Term Effects of Organic Amendments on Carbon Stability in Clay—Organic Complex and Its Role in Soil Aggregation. Agronomy. 13(1), 39. DOI: https://doi.org/10.3390/agronomy13010039

[52] Shalini, V., Chaithanya, A.K., Chandrashaker, K., et al., 2022. Microbial Biomass and Enzymatic Activity of Major Cropping Systems in Soils of Inceptisols and Vertisols at Northern Telangana. International Journal of Environment and Climate Change. 50–56. DOI: https://doi.org/10.9734/ijecc/2022/v12i530671

[53] Congreves, K., Wu, Q., Arcand, M.M., 2023. Biological Soil Health Indicators Constrained by Soil Classification But Improved by Regenerative Practices. DOI: https://doi.org/10.2139/ssrn.4596730

[54] Akça, E., Nagano, T., Kume, T., et al., 2022. Traditional Land Use Systems' Potential as the Framework for Soil Organic Carbon Plans and Policies. In: Meena, R.S., Rao, C.S., Kumar, A. (eds.). Plans and Policies for Soil Organic Carbon Management in Agriculture. Springer Nature. pp. 59–93. DOI: https://doi.org/10.1007/978-981-19-6179-3_3

[55] Mencel, J., Mocek-Płóciniak, A., Kryszak, A., 2022. Soil Microbial Community and Enzymatic Activity of Grasslands under Different Use Practices: A Review. Agronomy. 12(5), 1136. DOI: https://doi.org/10.3390/agronomy12051136

[56] Vikram, K., Chaudhary, H., Rao, K.S., 2024. SOC and TN fluctuations determine the variations in microbial enzymatic activities under diverse land use types in the Central Himalaya, India. CATENA. 240, 107958. DOI: https://doi.org/10.1016/j.catena.2024.107958

[57] Gebbers, R., Adamchuk, V.I., 2010. Precision Agriculture and Food Security. Science. 327(5967), 828–831. DOI: https://doi.org/10.1126/science.1183899

[58] Tyagi, I., Gupta, R., Upadhyay, D., et al., 2024. GreenGuard: Advanced Sensor Solutions for Enhanced Crop Health and Growth. In Proceedings of the 2024 International Conference on Signal Processing and Advance Research in Computing (SPARC), LUCKNOW, India, 12 September 2024; pp. 1–6. DOI: https://doi.org/10.1109/SPARC61891.2024.10829148

[59] Sushma, Y., Lakshmi, C.J., Rajesh, K., et al., 2024. IoT Based Soil Nutrient Monitoring and Analysis System. In Proceedings of the 2024 International Conference on IoT Based Control Networks and Intelligent Systems (ICICNIS), Bengaluru, India, 17 December

2024; pp. 348–353. DOI: https://doi.org/10.1109/ICICNIS64247.2024.10823219

[60] Getahun, S., Kefale, H., Gelaye, Y., 2024. Application of Precision Agriculture Technologies for Sustainable Crop Production and Environmental Sustainability: A Systematic Review. The Scientific World Journal. 2024(1), 2126734. DOI: https://doi.org/10.1155/2024/2126734

[61] Moharana, S., Rath, B.S., Nayak, R.K., 2025. Digital Soil Nutrient Mapping using Geo-spatial Technology—A Case Study in Khordha District of Odisha. Agricultural Science Digest - A Research Journal. DOI: https://doi.org/10.18805/ag.D-6106

[62] Vellingiri, A., Kokila, R., Nisha, P., et al., 2024. Harnessing GPS, Sensors, and Drones to Minimize Environmental Impact: Precision Agriculture. In: Thandekkattu, S.G., Vajjhala, N.R. (eds.). Advances in Business Information Systems and Analytics. IGI Global: Hershey, PA, USA. pp. 77–108. DOI: https://doi.org/10.4018/979-8-3693-5498-8.ch004

[63] Ambaru, B., Manvitha, R., Madas, R., 2025. Synergistic integration of remote sensing and soil metagenomics data: advancing precision agriculture through interdisciplinary approaches. Frontiers in Sustainable Food Systems. 8, 1499973. DOI: https://doi.org/10.3389/fsufs.2024.1499973

[64] Patle, T., Tomar, B., Parihar, S.S., et al., 2024. Nanotechnology-Based Soil Improvement and Conservation for Enhancement of Crop Production. In: Rajput, V.D., Singh, A., Ghazaryan, K., et al. (eds.), Advances in Environmental Engineering and Green Technologies. IGI Global: Hershey, PA, USA. pp. 217–236. DOI: https://doi.org/10.4018/979-8-3693-1890-4.ch011

[65] Hoareau, C.E., Kabeya, C., 2024. Soil Remediation by Nanotechnology: Valuating Materials, Mechanisms, and Environmental Impacts. Industrial and Domestic Waste Management. 4(2), 132–142. DOI: https://doi.org/10.53623/idwm.v4i2.534

[66] Majeed, M., Noor, W., Rasool, A., et al., 2024. Nanotechnology for Soil Remediation and Land Restoration. In: Rajput, V.D., Singh, A., Ghazaryan, K., et al. (eds.). Advances in Environmental Engineering and Green Technologies. IGI Global: Hershey, PA, USA. pp. 60–77. DOI: https://doi.org/10.4018/979-8-3693-1890-4.ch004

[67] Ghosh, D., Sarkar, M.M., Roy, S., 2024. Smart Fertilizers: The Prospect of Slow Release Nanofertilizers in Modern Agricultural Practices. In: Abd-Elsalam, K.A., Alghuthaymi, M.A. (eds.). Nanofertilizers for Sustainable Agroecosystems, Nanotechnology in the Life Sciences. Springer Nature: Cham, Switzerland. pp. 343–372. DOI: https://doi.org/10.1007/978-3-031-41329-2_13

[68] Bratovcic, A., Hikal, W.M., Said-Al Ahl, H.A.H., et al., 2021. Nanopesticides and Nanofertilizers and Agricultural Development: Scopes, Advances and Applications. Open Journal of Ecology. 11(04), 301–316. DOI: https://doi.org/10.4236/oje.2021.114022

[69] Kah, M., Tufenkji, N., White, J.C., 2019. Nano-enabled strategies to enhance crop nutrition and protection. Nature Nanotechnology. 14(6), 532–540. DOI: https://doi.org/10.1038/s41565-019-0439-5

[70] Rathore, A., Hasan, W., Ramesha N M, et al., 2024. Nanotech for Crop Protection: Utilizing Nanoparticles for Targeted Pesticide Delivery. UTTAR PRADESH JOURNAL OF ZOOLOGY. 45(6), 46–71. DOI: https://doi.org/10.56557/upjoz/2024/v45i63950

[71] Singh, P., Tomar, B., Patle, T., et al., 2024. Nanotechnology Solutions for Sustainable Pest and Disease Control for Sustainable Agriculture and Food Security. In: Rajput, V.D., Singh, A., Ghazaryan, K., et al. (eds.). Advances in Environmental Engineering and Green Technologies. IGI Global: London, UK. pp. 193–215. DOI: https://doi.org/10.4018/979-8-3693-1890-4.ch010

[72] Mohapatra, R., Giri, D., Krishnaveni, S.A., et al., 2024. Nanotechnology-based Materials for Sustainable Pest and Disease Control in Agriculture. UTTAR PRADESH JOURNAL OF ZOOLOGY. 45(21), 167–178. DOI: https://doi.org/10.56557/upjoz/2024/v45i214626

[73] Rafique, N., Mattoo, D., Muntazari, T.H., et al., 2022. Role of Geospatial Techniques in Soil Erosion Modelling in South Koel Basin, Jharkhand, India. In: Bhunia, G.S., Chatterjee, U., Lalmalsawmzauva, K.C., et al. (eds.). Anthropogeomorphology, Geography of the Physical Environment. Springer International Publishing: Cham, Switzerland. pp. 321–333. DOI: https://doi.org/10.1007/978-3-030-77572-8_16

[74] Dash, P.K., 2024. Remote sensing as a potential tool for advancing digital soil mapping, in: Remote Sensing of Soils. Elsevier: Amsterdam, Netherlands. pp. 357–370. DOI: https://doi.org/10.1016/B978-0-443-18773-5.00021-1

[75] Kaliraj, S., Shunmugapriya, S., Lakshumanan, C., et al., 2025. Flood risk zone mapping and future projections for the Thamirabarani river basin, Southern India: insights from decadal rainfall trends and GIS-based analytical hierarchy process technique. Natural Hazards. 121(5), 5327–5361. DOI: https://doi.org/10.1007/s11069-024-07007-z

[76] Rai, V., Singh, S., Tekam, Y., et al., 2023. Enhancing Soil Degradation Assessment through the Integration of GIS and RS: A Comprehensive Review. International Journal of Environment and Climate Change. 13(9), 2622–2632. DOI: https://doi.org/10.9734/ijecc/2023/v13i92559

[77] Tripathi, D.K., 2020. Soil Resource Inventory for

Meeting Challenges of Land Degradation: A Remote Sensing Approach. In: Sahdev, S., Singh, R.B., Kumar, M. (Eds.), Geoecology of Landscape Dynamics, Advances in Geographical and Environmental Sciences. Springer Singapore: Singapore, pp. 83–101. DOI: https://doi.org/10.1007/978-981-15-2097-6_7

[78] Dhanalakshmi, B., 2024. Soil Health Intelligence System using Multispectral Imaging and Advanced Deep Learning Techniques (SHIDS-ADLT). Communications on Applied Nonlinear Analysis. 31(6s), 417–426. DOI: https://doi.org/10.52783/cana.v31.1233

[79] Macfarlane, F., Robb, C., Coull, M., et al., 2024. A deep learning approach for high-resolution mapping of Scottish peatland degradation. European Journal of Soil Science. 75(4), e13538. DOI: https://doi.org/10.1111/ejss.13538

[80] Dalagnol, R., Wagner, F.H., Galvão, L.S., et al., 2023. Mapping tropical forest degradation with deep learning and Planet NICFI data. Remote Sensing of Environment. 298, 113798. DOI: https://doi.org/10.1016/j.rse.2023.113798

[81] Rani, S., Baloda, S., Dinesh, et al., 2024. AI-Driven Insights into Soil Physio-Chemical Properties. International Journal of Environment and Climate Change. 14(12), 834–845. DOI: https://doi.org/10.9734/ijecc/2024/v14i124666

[82] Hosseini, F.S., Seo, M.B., Razavi-Termeh, S.V., et al., 2023. Geospatial Artificial Intelligence (GeoAI) and Satellite Imagery Fusion for Soil Physical Property Predicting. Sustainability. 15(19), 14125. DOI: https://doi.org/10.3390/su151914125

[83] Rukhovich, D.I., Koroleva, P.V., Rukhovich, D.D., et al., 2022. Recognition of the Bare Soil Using Deep Machine Learning Methods to Create Maps of Arable Soil Degradation Based on the Analysis of Multi-Temporal Remote Sensing Data. Remote Sensing. 14(9), 2224. DOI: https://doi.org/10.3390/rs14092224

[84] Taqiyuddin, S., 2023. Evaluation of Biochar amendments on soil health and crop productivity in organic Strawberry (Fragaria × Ananassa) farming. International Journal of Horticulture and Food Science. 5(1), 111–113. DOI: https://doi.org/10.33545/26631067.2023.v5.i1b.200

[85] Voruganti, C., 2023. Biochar Applications in Soil Restoration: Enhancing Soil Health and Carbon Sequestration. Environmental Reports. 5(1), 1–4. DOI: https://doi.org/10.51470/ER.2023.5.1.01

[86] Li, X., Shen, Q., Zhang, D., et al., 2013. Functional Groups Determine Biochar Properties (pH and EC) as Studied by Two-Dimensional 13C NMR Correlation Spectroscopy. PLoS ONE. 8(6), e65949. DOI: https://doi.org/10.1371/journal.pone.0065949

[87] Khan, M.A., Basir, A., Shah, S.T., et al., 2024. Sustainable Soil Management in Alkaline Soils: The Role of Biochar and Organic Nitrogen in Enhancing Soil Fertility. DOI: https://doi.org/10.20944/preprints202410.1189.v1

[88] Gross, A., Bromm, T., Polifka, S., et al., 2025. Long-term biochar and soil organic carbon stability-evidence from long-term field experiments in Germany. DOI: https://doi.org/10.5194/egusphere-egu24-9944

[89] Bai, X., Tang, J., Wang, W., et al., 2023. Organic amendment effects on cropland soil organic carbon and its implications: A global synthesis. CATENA. 231, 107343. DOI: https://doi.org/10.1016/j.catena.2023.107343

[90] Li, Q., Xu, M., Xu, L., et al., 2025. Organic Fertilization Leads to N Limitation Rather than P Limitation in Both Vegetable Soils. Agronomy. 15(1), 190. DOI: https://doi.org/10.3390/agronomy15010190

[91] Bah, H., Zhou, M., Kizito, S., et al., 2020. Carbon Balance under Organic Amendments in the Wheat-Maize Cropping Systems of Sloppy Upland Soil. Sustainability. 12(7), 2747. DOI: https://doi.org/10.3390/su12072747

[92] Chourasiya, D., Sharma, M.P., Maheshwari, H.S., et al., 2017. Microbial Diversity and Soil Health in Tropical Agroecosystems. In: Adhya, T.K., Mishra, B.B., Annapurna, K., et al. (eds.). Advances in Soil Microbiology: Recent Trends and Future Prospects, Microorganisms for Sustainability. Springer Singapore, Singapore, pp. 19–35. DOI: https://doi.org/10.1007/978-981-10-7380-9_2

[93] Jiang, D., Wu, C., Wang, S., et al., 2023. Vermicompost derived from mushroom residues improves soil C/P cycling, bacterial community, and fungal abundance. GCB Bioenergy. 15(12), 1437–1449. DOI: https://doi.org/10.1111/gcbb.13103

[94] Karmakar, S., Acharya, R., Roy, D.B., et al., 2024. Sustainable Management of Organic Wastes to Enhance Soil Health via Vermicomposting. In: A Basic Overview of Environment and Sustainable Development. International Academic Publishing House (IAPH): London, UK. pp. 1–19. DOI: https://doi.org/10.52756/boesd.2024.e03.001

[95] Prabhu, A., Prakash, S., 2023. The Role of Microflora (Bacteria) and their Relationship with Macrofauna (Earthworms) in Vermicompost: A Review. International Journal of Science and Research (IJSR). 12(2), 1309–1320. DOI: https://doi.org/10.21275/SR23221221614

[96] Abioye, O.M., Amodu, M.F., Raphael, D.O., et al., 2024. An Overview of the Role of Vermicompost in Reducing Green House Gas Emissions, Improving Soil Health, and Increasing Crop Yields. Applied Science and Engineering Progress. DOI: https://doi.org/10.14416/j.asep.2024.09.011

[97] Nakhli, S.A.A., Delkash, M., Bakhshayesh, B.E., et

al., 2017. Application of Zeolites for Sustainable Agriculture: a Review on Water and Nutrient Retention. Water, Air, & Soil Pollution. 228(12), 464. DOI: https://doi.org/10.1007/s11270-017-3649-1

[98] Oladosu, Y., Rafii, M.Y., Arolu, F., et al., 2022. Superabsorbent Polymer Hydrogels for Sustainable Agriculture: A Review. Horticulturae. 8(7), 605. DOI: https://doi.org/10.3390/horticulturae8070605

[99] Zhang, Y., Tian, X., Zhang, Q., et al., 2022. Hydrochar-embedded carboxymethyl cellulose-g-poly(acrylic acid) hydrogel as stable soil water retention and nutrient release agent for plant growth. Journal of Bioresources and Bioproducts. 7(2), 116–127. DOI: https://doi.org/10.1016/j.jobab.2022.03.003

[100] Naushabayev, A.K., VassiliNa, T.K., Rsymbetov, B.A., et al., 2022. Effects of different polymer hydrogels on moisture capacity of sandy soil. EURASIAN JOURNAL OF SOIL SCIENCE (EJSS). 11(3), 241–247. DOI: https://doi.org/10.18393/ejss.1078342

[101] Lal, R., 2015. Restoring Soil Quality to Mitigate Soil Degradation. Sustainability. 7(5), 5875–5895. DOI: https://doi.org/10.3390/su7055875

[102] Chivenge, P., Vanlauwe, B., Six, J., 2011. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant and Soil. 342(1–2), 1–30. DOI: https://doi.org/10.1007/s11104-010-0626-5

[103] Bhattacharyya, R., Prakash, V., Kundu, S., et al., 2009. Soil aggregation and organic matter in a sandy clay loam soil of the Indian Himalayas under different tillage and crop regimes. Agriculture, Ecosystems & Environment. 132(1–2), 126–134. DOI: https://doi.org/10.1016/j.agee.2009.03.007

[104] Edmeades, D.C., 2003. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutrient Cycling in Agroecosystems. 66(2), 165–180. DOI: https://doi.org/10.1023/A:1023999816690

[105] Lorenz, K., Lal, R., 2016. Environmental Impact of Organic Agriculture, in: Advances in Agronomy. 139, 99–152. DOI: https://doi.org/10.1016/bs.agron.2016.05.003

[106] Leifeld, J., Fuhrer, J., 2010. Organic Farming and Soil Carbon Sequestration: What Do We Really Know About the Benefits? AMBIO. 39(8), 585–599. DOI: https://doi.org/10.1007/s13280-010-0082-8

[107] Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development. 30(2), 401–422. DOI: https://doi.org/10.1051/agro/2009040

[108] Lehmann, J., Bossio, D.A., Kögel-Knabner, I., et al., 2020. The concept and future prospects of soil health. Nature Reviews Earth & Environment. 1(10), 544–553. DOI: https://doi.org/10.1038/s43017-020-0080-8

[109] Maeder, P., Fliessbach, A., Dubois, D., et al., 2002. Soil Fertility and Biodiversity in Organic Farming. Science. 296(5573), 1694–1697. DOI: https://doi.org/10.1126/science.1071148

[110] Ding, J., Ma, M., Jiang, X., et al., 2020. Effects of applying inorganic fertilizer and organic manure for 35 years on the structure and diversity of ammonia-oxidizing archaea communities in a Chinese Mollisols field. MicrobiologyOpen. 9(1), e942. DOI: https://doi.org/10.1002/mbo3.942

[111] Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. Nature Plants. 2(2), 15221. DOI: https://doi.org/10.1038/nplants.2015.221

[112] Amante, G., Wedajo, M., 2024. Impacts of Climate change on soil microbial diversity, distribution and abundance. International Journal on Food, Agriculture and Natural Resources. 5(2), 158–168. DOI: https://doi.org/10.46676/ij-fanres.v5i2.342

[113] Khursheed, S., 2016. Soil Biodiversity and Climate Change. Advances in Plants & Agriculture Research. 3(5). DOI: https://doi.org/10.15406/apar.2016.03.00113

[114] Borah, B., Parmar, P., 2024. Soil Organic Carbon Dynamics: Drivers of Climate Change-induced Soil Organic Carbon Loss at Various Ecosystems. International Journal of Environment and Climate Change. 14(10), 153–174. DOI: https://doi.org/10.9734/ijecc/2024/v14i104477

[115] Qafoku, N.P., 2015. Climate-Change Effects on Soils: Accelerated Weathering, Soil Carbon, and Elemental Cycling. In: Advances in Agronomy. Elsevier: Amsterdam, Netherlands. pp. 111–172. DOI: https://doi.org/10.1016/bs.agron.2014.12.002

[116] Wang, X., Zhang, Q., Zhang, Z., et al., 2023. Decreased soil multifunctionality is associated with altered microbial network properties under precipitation reduction in a semiarid grassland. iMeta. 2(2), e106. DOI: https://doi.org/10.1002/imt2.106

[117] Sanaullah, M., Afzal, T., 2022. Soil organic carbon sequestration and climate change. In: Rumpel, C. (ed.). Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing, pp. 237–270. DOI: https://doi.org/10.19103/AS.2022.0106.08

[118] Das, R., Ghosh, A., Das, S., et al., 2021. Soil Carbon Sequestration for Soil Quality Improvement and Climate Change Mitigation. In: Pant, D., Kumar Nadda, A., Pant, K.K., et al. (eds.). Advances in Carbon Capture and Utilization, Energy, Environment, and Sustainability. Springer Singapore: Singapore, pp. 57–81. DOI: https://doi.org/10.1007/978-981-16-0638-0_4

[119] Lal, R., 2018. Soil and Climate. In: Lal, R., Stewart, B.A. (eds.). Soil and Climate. CRC Press: Boca Raton, FL, USA. pp. 1–10. DOI: https://doi.org/10.1201/b21225-1

[120] Bayata, A., Mulatu, G., 2024. Carbon Farming, Climate Smart Agriculture Practice and Current Climate Change Mitigation Strategy- In the Case of Ethiopia. International Journal of Environmental Monitoring and Analysis. 12(6), 149–156. DOI: https://doi.org/10.11648/j.ijema.20241206.12

[121] Hailu, L., Teka, W., 2024. Potential of conservation agriculture practice in climate change adaptation and mitigation in Ethiopia: a review. Frontiers in Climate. 6, 1478923. DOI: https://doi.org/10.3389/fclim.2024.1478923

[122] Sisay, T., Tesfaye, K., Ketema, M., et al., 2023. Climate-Smart Agriculture Technologies and Determinants of Farmers' Adoption Decisions in the Great Rift Valley of Ethiopia. Sustainability. 15(4), 3471. DOI: https://doi.org/10.3390/su15043471

[123] Erekalo, K.T., Yadda, T.A., 2023. Climate-smart agriculture in Ethiopia: Adoption of multiple crop production practices as a sustainable adaptation and mitigation strategies. World Development Sustainability. 3, 100099. DOI: https://doi.org/10.1016/j.wds.2023.100099

[124] Seo, N., Mendelsohn, R., Dinar, A., et al., 2008. Long-Term Adaptation: Selecting Farm Types Across Agro-Ecological Zones In Africa. World Bank: Washington, DC, USA. DOI: https://doi.org/10.1596/1813-9450-4602

[125] Hellin, J., Fisher, E., Taylor, M., et al., 2023. Transformative adaptation: from climate-smart to climate-resilient agriculture. CABI Agriculture and Bioscience. 4(1), 30. DOI: https://doi.org/10.1186/s43170-023-00172-4

[126] Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil and Tillage Research. 66(2), 95–106. DOI: https://doi.org/10.1016/S0167-1987(02)00018-1

[127] Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. Agriculture, Ecosystems & Environment. 200, 33–41. DOI: https://doi.org/10.1016/j.agee.2014.10.024

[128] Gattinger, A., Muller, A., Haeni, M., et al., 2012. Enhanced top soil carbon stocks under organic farming. Proceedings of the National Academy of Sciences. 109(44), 18226–18231. DOI: https://doi.org/10.1073/pnas.1209429109