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ADVANCES IN SOIL HEALTH ASSESSMENT: INTEGRATING TECHNOLOGIES FOR SUSTAINABLE AGRICULTURE

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ABSTRACT

In recent years, soil health assessment has emerged as a critical component of sustainable soil management, essential for optimizing agricultural productivity, ecosystem services and environmental resilience. This paper reviews the latest developments in soil health assessment techniques, emphasizing multidimensional indicators and their practical applications. Novelty in this research lies in its comprehensive synthesis of recent advancements across physical, chemical, and biological dimensions of soil health assessment. It explores innovative techniques such as electromagnetic induction (EMI) and remote sensing, which provide high-resolution data for precise soil mapping and management. The integration of these multidimensional indicators enhances the accuracy and reliability of soil health evaluations, supporting tailored agricultural practices and environmental conservation efforts. Soil health, characterized by its ability to sustain nutrient cycling, water retention and carbon storage is critically analyzed through physical indicators like soil structure and aggregate stability, chemical indicators such as pH and nutrient availability and biological indicators including microbial diversity and activity. This holistic approach not only advances scientific understanding but also offers practical insights for improving soil management strategies globally. By synthesizing current research and highlighting innovative methodologies; this paper contributes to advancing soil health science and promoting sustainable agricultural practices. It underscores the importance of multidisciplinary approaches in assessing soil health, thereby supporting resilient ecosystems and ensuring food security amidst ongoing environmental changes.

Key words : Soil health assessment, Sustainable soil management, Multidimensional indicators, Electromagnetic induction (EMI), Remote sensing, Agricultural productivity.

Introduction

Natural soil functions as a dynamic ecosystem essential for supporting plant growth, regulating nutrient cycles, managing water resources and sequestering carbon dioxide. The concept of soil health has gained significant traction in recent years as a pivotal aspect of sustainable land management practices. Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply-chain management (Lehmann *et al.*, 2020). It serves as a fundamental indicator of ecosystem resilience and productivity, influencing agricultural sustainability and environmental quality on a global scale.

The assessment of soil health involves evaluating a range of interrelated physical, chemical, and biological properties. Physical indicators such as soil structure, texture, and aggregate stability determine the soil's ability to facilitate root penetration, water infiltration, and resist erosion (Seifu and Elias, 2018). Chemical indicators like pH, nutrient levels, and cation exchange capacity (CEC) reflect soil fertility and nutrient availability, crucial for supporting plant growth and optimizing agricultural outputs (Seifu and Elias, 2018; Trigunasih, 2023). Biological indicators, including microbial diversity, biomass and enzyme activities, indicate soil biological activity and its role in nutrient cycling and organic matter decomposition (Nikitin *et al*., 2022; Neemisha and Sharma, 2022).

Recent advancements in soil health assessment techniques have expanded our ability to comprehensively evaluate these indicators. Innovations such as electromagnetic induction (EMI) and remote sensing technologies provide precise and non-invasive methods for mapping soil properties over large spatial scales (Pathirana *et al*., 2023; Pradipta *et al*., 2022). These technological advancements enhance our understanding of soil variability and inform site-specific management strategies in agriculture.

This paper reviews the latest developments in soil health assessment techniques, emphasizing their multidimensional nature and practical applications in sustainable land management. By synthesizing current research and highlighting innovative methodologies, it aims to contribute to the advancement of soil health science and promote informed decision-making for resilient agricultural systems in a changing climate.

I. Multitier Soil Health Indicators

Multitier Soil Health Indicators encompass a range of biological, physical and chemical indicators essential for comprehensive soil health evaluation.

1. Biological Indicators

Biological indicators play a crucial role in evaluating soil health by assessing microbial diversity, activity and community structure. These indicators provide insights into soil fertility, nutrient cycling dynamics and overall ecosystem functioning. The following points detail various biological indicators commonly used in soil health assessments:

A. Microbial Diversity

Microbial diversity in soil refers to the richness and abundance of microorganisms, including bacteria, fungi, and archaea, which are fundamental to soil health and ecosystem functioning. The diversity of these microbial communities is crucial as it indicates the resilience and stability of soil ecosystems. Higher microbial diversity is generally associated with increased ecosystem productivity and nutrient cycling capabilities. For example, a study by Yadav *et al*. (2021) highlighted that diverse microbial communities can perform a wider range of functions, such as organic matter decomposition, nitrogen fixation, and nutrient mineralization, which are essential for sustaining plant growth and soil fertility.

Techniques such as phospholipid fatty acid (PLFA) analysis and DNA sequencing (metagenomics) are pivotal in assessing microbial diversity and community composition. PLFA analysis provides insights into the structure and composition of microbial membranes, indicating the presence and relative abundance of different microbial groups (Li *et al*., 2020; Nkongolo *et al*., 2020). On the other hand, metagenomics allows for the comprehensive genetic characterization of microbial communities, revealing their functional potential and metabolic pathways in the soil environment (Nesme *et al*., 2016; Jansson and Hofmockel, 2018).

Understanding microbial diversity is crucial for predicting soil-plant interactions and nutrient cycling dynamics. For instance, specific microbial taxa play key roles in nutrient transformation processes, such as nitrogen cycling (Nelson *et al*., 2016; Robertson and Groffman, 2024). By quantifying microbial diversity through advanced molecular techniques, researchers can decipher the intricate relationships between soil microorganisms, plants, and soil nutrients. Moreover, microbial diversity serves as an indicator of soil health and resilience against environmental stresses. Diverse microbial communities are more adaptable to changes in environmental conditions, such as temperature fluctuations or pollution events (Bardgett and Caruso, 2020; Philippot *et al*., 2024). This adaptability enhances the overall stability and sustainability of agricultural and natural ecosystems.

Thus, microbial diversity in soil is critical for maintaining soil fertility, supporting plant growth and sustaining ecosystem services. Advances in analytical techniques continue to deepen our understanding of microbial communities and their roles in soil ecosystems, providing valuable insights for sustainable soil management practices.

B. Microbial Biomass and Activity

Microbial biomass and activity are critical indicators of soil biological fertility and nutrient cycling efficiency, reflecting the metabolic functions of microorganisms essential for ecosystem health. These parameters provide valuable insights into the capacity of soils to support plant growth and sustain agricultural productivity. Microbial biomass carbon (MBC) is a measure of the total carbon content within microbial cells in soil. It serves as an indicator of the microbial pool actively involved in nutrient transformations and organic matter decomposition (Paul, 2016). Higher MBC levels often correlate with increased soil fertility and nutrient availability, as microbes play crucial roles in mineralizing organic nutrients into forms that plants can absorb (Nguyen and Marschner, 2017).

Methods such as substrate-induced respiration (SIR) and chloroform fumigation-extraction are commonly employed to assess microbial biomass and activity. SIR measures the rate of carbon dioxide (CO_2) released by soil microorganisms when provided with specific carbon substrates, indicating their metabolic activity and biomass turnover rates (Xue, 2017). Chloroform fumigation-extraction involves sterilizing soil samples with chloroform to estimate the difference in organic carbon content before and after fumigation, providing an indirect measure of microbial biomass (Brookes *et al.*, 2017). Microbial respiration rates, measured through these techniques, reflect the overall microbial activity in soil and their contribution to nutrient cycling dynamics. High respiration rates indicate active microbial communities capable of efficiently decomposing organic matter and releasing nutrients such as nitrogen and phosphorus into forms usable by plants (Biswas and Kole, 2017; Chernov and Semenov, 2021).

For example, in agricultural systems, understanding microbial biomass and activity helps optimize fertilizer applications and soil management practices to enhance nutrient use efficiency and minimize environmental impacts (Bargaz *et al.*, 2018). Healthy soil microbial communities contribute to sustainable crop production by maintaining soil structure, suppressing pathogens and improving water retention (Chen *et al.*, 2022).

In summary, microbial biomass and activity measurements are integral to assessing soil health and fertility, providing quantitative data on microbial functions crucial for nutrient cycling and ecosystem sustainability. Advances in methodologies continue to refine our understanding of microbial contributions to soil processes, supporting informed decisions in agricultural and environmental management.

C. Enzyme Activities

Enzyme activities such as β-glucosidase, urease and phosphatase play pivotal roles in catalyzing biochemical reactions crucial for nutrient cycling and organic matter decomposition in soil ecosystems. These enzymes are indicators of soil health, providing insights into the availability and cycling of nutrients essential for plant growth and ecosystem sustainability. β-glucosidase is involved in the hydrolysis of â-glucosides, releasing glucose which serves as a carbon source for microorganisms and plants (Burns *et al.*, 2013). Urease catalyzes the hydrolysis of urea into ammonia and carbon dioxide, making nitrogen available for plant uptake and microbial assimilation (Joseph *et al.*, 2022). Phosphatase enzymes hydrolyze organic phosphorus compounds, releasing phosphate ions that are crucial for plant growth and metabolic processes (Richardson and Simpson, 2011). Assessing these enzymes through specific assays provides quantitative measures of their activities in soil. For instance, fluorometric assays or colorimetric methods are commonly used to quantify enzyme activities, reflecting the metabolic capabilities of soil microbial communities (Hoehn, 2016). These assays are sensitive indicators of soil microbial activity and their contributions to nutrient mineralization and availability. Studies have shown that enzyme activities in soil can vary significantly with changes in environmental factors such as soil pH, moisture content, and organic matter inputs (Burns *et al.*, 2013). Monitoring these enzymatic processes provides valuable information on soil fertility dynamics and nutrient cycling efficiency. High enzyme activities generally indicate nutrient-rich and biologically active soils capable of supporting vigorous plant growth and sustainable agricultural practices (Bruns and Couradeau, 2021).

For example, in agroecosystems, understanding enzyme dynamics helps optimize fertilizer management strategies and improve nutrient use efficiency (Bruns *et al.*, 2013). Enzyme assays also aid in assessing the impacts of land management practices, such as tillage and organic amendments, on soil health and ecosystem functioning (Acosta-Martínez *et al.*, 2010). In essence, enzyme activities such as β-glucosidase, urease and phosphatase are critical biochemical indicators of soil health and nutrient availability. Their assessment through specific assays provides quantitative insights into soil microbial activity and their roles in nutrient cycling processes essential for sustainable agriculture and ecosystem management.

D. Earthworms and Soil Fauna

Earthworms and other soil fauna play crucial roles in maintaining soil health by contributing to nutrient cycling, enhancing soil structure, and facilitating organic matter decomposition (Akhila and Entoori, 2022). These organisms are indicators of a healthy soil ecosystem due to their diverse ecological functions. Earthworms, for example, are known for their ability to ingest soil and organic matter, processing it through their digestive system and excreting nutrient-rich casts that improve soil fertility (Singh, 2018). Their burrowing activities also enhance soil structure by creating channels that improve water infiltration and root penetration (Blouin *et al.*, 2013). This process, known as bioturbation, helps aerate the soil and promote the movement of nutrients and gases within the soil profile (Le Bayon *et al.*, 2021).

In addition to earthworms, other soil fauna such as insects, mites, nematodes and microarthropods contribute to nutrient cycling through their feeding activities and interactions with soil microbes (Lakshmi *et al.*, 2020). For instance, microarthropods like springtails and mites break down organic matter into smaller particles, facilitating its decomposition and releasing nutrients back into the soil (Raza *et al.*, 2019). The presence and abundance of earthworms and soil fauna serve as indicators of soil biological health and overall ecosystem resilience. Studies have shown that diverse communities of soil organisms contribute to the stability and productivity of agricultural and natural ecosystems (de Vries *et al.*, 2013). Their activities not only improve soil fertility and structure but also enhance the capacity of soils to resist environmental stressors such as drought and erosion (Le Bayon *et al.*, 2021). Therefore, monitoring earthworm populations and the diversity of soil fauna provides valuable insights into soil health and ecosystem functioning. These indicators help assess the sustainability of agricultural practices and guide management strategies aimed at enhancing soil biodiversity and productivity.

E. Mycorrhizal Fungi

Mycorrhizal fungi establish symbiotic associations with plant roots, forming intricate networks that significantly enhance nutrient uptake, especially phosphorus, and improve soil structure. These fungi play pivotal roles in soil ecosystems by facilitating nutrient exchange between plants and the soil, thereby influencing plant growth and ecosystem productivity (Wahab *et al.*, 2023). The symbiotic relationship involves the fungal hyphae extending far beyond the root zone, effectively increasing the surface area for nutrient absorption and enhancing the plant's access to water and minerals (Kleinert *et al.*, 2018). This nutrient exchange is particularly beneficial in nutrient-poor soils where mycorrhizal associations can substantially improve plant growth and health (Smith and Read, 2008).

Assessing mycorrhizal colonization rates and fungal diversity provides critical insights into soil fertility and plant nutrient acquisition efficiency. High levels of mycorrhizal colonization are indicative of soil conditions favorable for plant growth, as they enhance nutrient availability and support plant resilience against environmental stresses (van der Heijden *et al.*, 2015). Furthermore, diverse mycorrhizal communities contribute to ecosystem stability and function by promoting soil aggregation and enhancing carbon sequestration (Xu *et al.*, 2017). In agricultural contexts, understanding mycorrhizal associations helps optimize nutrient management strategies and reduce dependency on synthetic fertilizers, thereby promoting sustainable farming practices (Bargaz *et al.*, 2018). Mycorrhizal fungi also play a crucial role in ecosystem restoration efforts, facilitating plant establishment and growth in degraded landscapes (Asmelash *et al.*, 2016).

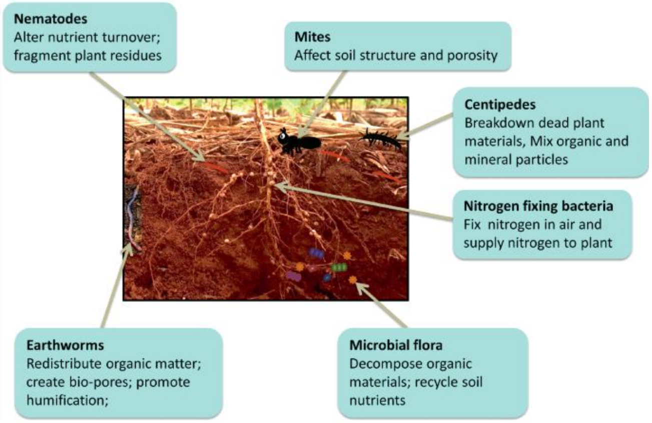

Fig. 1 : Biological indicators of soil health (Source: Dahiya *et al*, 2022).

Ultimately, mycorrhizal fungi represent integral components of soil health assessment, providing a holistic perspective on microbial dynamics, nutrient cycling processes and ecosystem resilience. Their symbiotic relationships with plants underscore their importance in sustainable agriculture and environmental conservation efforts.

2. Physical Indicators

Physical indicators evaluate soil structure, texture, and aggregate stability, crucial for processes like water infiltration, root penetration, and erosion resistance. Techniques such as soil particle size analysis and bulk density measurement provide insights into soil physical properties (Romero-Rutz *et al.*, 2018). These indicators are pivotal in assessing soil physical integrity and its implications for crop productivity and environmental sustainability.

A. Soil Structure

The arrangement of soil particles into aggregates, known as soil structure is a fundamental determinant of soil health and agricultural productivity. It significantly influences key soil functions such as aeration, water movement, nutrient availability and root development. Good soil structure is characterized by well-formed aggregates that create pore spaces essential for air and water movement within the soil profile. This facilitates optimal aeration, crucial for the respiration of roots and soil organisms, and for the maintenance of aerobic conditions necessary for nutrient cycling [Natural Resources Conservation Service (NRCS), n.d.]. Adequate soil aeration also supports microbial activity, which plays a central role in organic matter decomposition and nutrient mineralization processes (Li *et al.*, 2020).

Furthermore, soil structure directly impacts water infiltration rates, determining the ability of water to enter and move through the soil. Well-structured soils with good aggregation allow for rapid infiltration of water, reducing surface runoff and enhancing water retention in the root zone (Bouma *et al.*, 2020)). This improves soil moisture availability for plant uptake and mitigates risks associated with waterlogging and drought stress. Root growth and development are also profoundly influenced by soil structure. Soil aggregates provide a favorable environment for root exploration, allowing roots to penetrate deeper and access nutrients and water efficiently (Bronick and Lal, 2005; Lynch *et al.*, 2022). In contrast, compacted soils with poor structure hinder root growth and limit nutrient uptake, thereby compromising plant health and productivity (NRCS, n.d.).

Studies have demonstrated that soil structure management practices, such as reduced tillage and cover cropping, can enhance soil aggregation and improve overall soil health (Bronick and Lal, 2005; Farmaha *et al.*, 2022). These practices promote the formation and stabilization of soil aggregates, contributing to long-term soil fertility and sustainability in agricultural systems (Angon *et al.*, 2023). Therefore, it can be concluded that soil structure serves as a critical indicator of soil health due to its profound influence on essential soil functions and crop productivity. Understanding and managing soil structure are essential for optimizing agricultural practices, conserving soil resources, and ensuring sustainable food production systems for future generations.

B. Soil Texture

Soil texture is a critical indicator of soil health and fertility due to its influence on various soil properties essential for plant growth and ecosystem sustainability. While it cannot be directly altered due to its inherent mineral composition, understanding soil texture guides effective soil management practices aimed at optimizing agricultural productivity and environmental stewardship. The distribution of these particles affects water retention, drainage characteristics, soil aeration, and nutrient availability, all of which are essential for sustaining agricultural productivity and environmental quality (Enriqueta Arias *et al.*, 2005). The size of soil particles determines the soil’s capacity to hold water and nutrients. Sandy soils, characterized by larger particles, have good drainage but lower water-holding capacity and nutrient retention compared to finer-textured soils such as clay (Brady and Weil, 2008). Conversely, clay soils retain water well but can be poorly aerated, affecting root growth and microbial activity (Brady and Weil, 2008). Water intake rates in the soil are influenced by texture, with sandy soils allowing rapid infiltration but potentially leading to leaching of nutrients, while clayey soils may experience slower infiltration rates and waterlogging under certain conditions (Enriqueta Arias *et al.*, 2005). Optimal soil texture balances water availability for plant uptake and drainage to prevent waterlogging, ensuring favorable conditions for root development and microbial processes essential for nutrient cycling (Brady and Weil, 2008).

Root development is significantly influenced by soil texture, as roots navigate through the soil matrix in search of water, nutrients, and oxygen. Soil texture affects root penetration and branching, with fine-textured soils generally offering greater resistance to root growth compared to coarser-textured soils (Brady and Weil, 2008). Understanding these dynamics helps in selecting appropriate crops and management practices to maximize root exploration and nutrient uptake efficiency in different soil types (Lipiec *et al.*, 2012). Moreover, soil texture influences microbial activities crucial for organic matter decomposition and nutrient cycling. Microorganisms in soils interact differently with particles of varying sizes, affecting their metabolic rates and contributions to soil fertility (Brady and Weil, 2008). For example, microbial communities in sandy soils may exhibit faster turnover rates due to enhanced aeration and nutrient availability, while those in clayey soils may play a role in stabilizing organic matter and retaining nutrients over longer periods (Six *et al.*, 2004).

In agricultural and environmental management, soil texture assessments guide decisions on irrigation scheduling, nutrient management and soil amendment applications tailored to specific soil types (Lipiec *et al.*, 2012). Sustainable soil management practices aim to enhance soil texture properties through practices like organic matter additions and cover cropping, thereby improving overall soil health and resilience to environmental stresses (Powlson *et al.*, 2011; Techne *et al.*, 2020). In short, soil texture serves as a crucial indicator of soil health, influencing water dynamics, root growth, microbial activities and overall soil fertility. Managing soil texture through informed agricultural practices is essential for maintaining productive and sustainable land use systems.

C. Aggregate Stability

Aggregate stability serves as a crucial indicator of soil health, reflecting the ability of soil aggregates to resist physical disruption and maintain structural integrity under various environmental stresses. It directly influences soil functionality by influencing water infiltration, nutrient cycling, and overall ecosystem resilience [Sustainable Agriculture Research & Education (SARE), n.d.]. For example, in agricultural systems, soils with high aggregate stability exhibit reduced erosion rates as stable aggregates are less prone to breakdown by raindrops and runoff, thereby preserving soil structure and preventing loss of fertile topsoil (De Ploey and Poesen, 2020). This phenomenon is essential for sustaining crop productivity and minimizing off-site impacts such as sedimentation in water bodies. Moreover, stable aggregates create favorable microenvironments for soil organisms, promoting biodiversity and enhancing soil fertility through efficient nutrient cycling processes (Le Bissonnais, 2023).

Enhancing aggregate stability involves adopting soil management practices that promote organic matter accumulation, minimize soil disturbance through reduced tillage, and encourage the presence of soil biota that contribute to aggregate formation and stabilization (Zhou *et al.*, 2020). These practices not only improve soil physical properties but also contribute to long-term soil health and sustainability in agricultural and natural ecosystems alike.

D. Bulk Density

Bulk density serves as a critical metric for assessing soil health, providing insights into soil compaction, porosity, and overall suitability for plant growth and ecosystem functioning. Defined as the mass of soil per unit volume, bulk density influences root penetration, water infiltration rates and nutrient availability [Sustainable Agriculture Research & Education (SARE), n.d.]. For instance, soils with high bulk density often exhibit reduced pore space, limiting water retention and air exchange crucial for microbial activity and root growth (Priori *et al.*, 2020; Oliveira *et al.*, 2024). This compaction can lead to increased runoff and erosion risk, diminishing soil fertility and productivity over time.

Managing bulk density involves practices that mitigate soil compaction, such as reducing machinery traffic, adopting minimum tillage techniques and incorporating organic matter to enhance soil structure (Rahman *et al.*, 2020). These practices not only improve water and nutrient availability but also promote root development and microbial diversity, contributing to sustained agricultural productivity and ecosystem resilience. Monitoring changes in bulk density over time provides valuable feedback on the effectiveness of soil management strategies in maintaining or improving soil health and productivity.

E. Water Infiltration Rate

Water infiltration rate is a fundamental indicator of soil health, influencing the ability of soil to absorb and retain water essential for plant growth, groundwater recharge, and ecosystem stability [Sustainable Agriculture Research & Education (SARE), n.d.]. This parameter reflects soil structure, porosity, and organic matter content, all of which play critical roles in determining infiltration capacity. For instance, soils rich in organic matter and well-aggregated exhibit higher infiltration rates due to improved soil structure that enhances macropore formation and water movement through the soil profile (Adeyemo *et al.*, 2019). Conversely, compacted soils or those with low organic matter content often experience reduced infiltration rates, leading to increased surface runoff, erosion and diminished water availability for plants.

Effective soil management practices can enhance water infiltration rates by promoting soil structure improvement and organic matter accumulation. Techniques such as cover cropping, reduced tillage and agroforestry contribute to maintaining soil porosity and reducing compaction, thereby enhancing infiltration capacity (Griffiths *et al.*, 2018). Monitoring changes in water infiltration rates provides insights into soil health dynamics and the effectiveness of management practices in mitigating water-related challenges in agricultural and natural ecosystems

F. Soil Penetration Resistance

Soil penetration resistance, often used as an indicator of soil health, reflects the ease with which roots can penetrate the soil profile, influencing plant growth, water infiltration, and nutrient availability [Sustainable Agriculture Research & Education (SARE), n.d.]. High soil penetration resistance indicates compacted soil conditions, which restrict root elongation and reduce access to water and nutrients (Lipiec *et al.*, 2012). Compacted soils also impede water infiltration, leading to increased surface runoff and erosion risks, thereby diminishing soil productivity and ecosystem resilience over time.

Effective soil management practices aim to mitigate soil compaction and enhance soil penetration for improved plant growth and soil health. Techniques such as deep tillage, cover cropping, and incorporation of organic matter help to alleviate soil compaction by promoting soil structure and porosity (Bronick and Lal, 2005; Zhang *et al.*, 2021). Monitoring soil penetration resistance provides valuable insights into soil physical conditions and guides management decisions aimed at maintaining or improving soil health and productivity in agricultural and natural environments

G. Susceptibility to Erosion

Susceptibility to erosion is a critical measure of soil health, reflecting the ability of soil to resist erosion processes driven by wind, water, or tillage practices. Soil erosion can lead to loss of topsoil, nutrient depletion, reduced water holding capacity, and degradation of soil structure, all of which negatively impact agricultural productivity and environmental quality (Montgomery, 2007). High susceptibility to erosion often correlates with poor soil management practices such as intensive tillage, inadequate vegetative cover and steep slopes, which compromise soil stability and expose it to erosive forces [Sustainable Agriculture Research & Education (SARE), n.d.]. For instance, in regions with extensive monoculture farming and minimal soil conservation measures, erosion rates can accelerate, resulting in decreased crop yields and sedimentation of water bodies.

Effective erosion control strategies include implementing conservation practices like contour farming, terracing, cover cropping, and reducing soil disturbance through no-till agriculture (Seitz *et al.*, 2020). These practices help to preserve soil structure, enhance organic matter content, and promote vegetation cover, thereby reducing erosion risks and improving overall soil health. Monitoring and assessing soil susceptibility to erosion provide essential feedback for guiding land management decisions aimed at sustainable agriculture and natural resource conservation.

3. Chemical Indicators

Chemical indicators assess soil nutrient status, pH levels and the presence of contaminants. Methods like soil nutrient analysis using spectrophotometry or ion chromatography quantify essential nutrients and heavy metals affecting plant growth (Mehlich, 1984; Collins *et al.*, 2001; Omeje *et al.*, 2021). Understanding these indicators aid in making informed decisions regarding nutrient management and soil remediation strategies.

A. pH Levels

The pH level of soil is a crucial indicator of soil health, influencing nutrient availability, microbial activity and overall plant growth. Soil pH determines the solubility of essential nutrients such as phosphorus, potassium and calcium, with optimal pH ranges varying for different crops and plants [Sustainable Agriculture Research & Education (SARE), n.d.]. For example, acidic soils with low pH can limit the availability of nutrients like phosphorus and manganese, affecting plant growth and productivity (Marschner, 2011). On the other hand, excessively alkaline soils can reduce the availability of micronutrients such as iron and zinc, impairing plant health despite sufficient nutrient levels in the soil (Khan *et al.*, 2015).

Managing soil pH involves practices such as liming to raise pH in acidic soils or incorporating organic matter to buffer pH fluctuations. These strategies not only enhance nutrient availability but also support beneficial microbial communities that contribute to soil fertility and structure (Philippot *et al.*, 2024). Monitoring and maintaining optimal soil pH levels are essential for sustainable agriculture, ensuring that crops receive the necessary nutrients for healthy growth while minimizing environmental impacts such as nutrient leaching and soil degradation.

B. Electrical Conductivity (EC)

Electrical conductivity (EC) serves as a significant indicator of soil health, reflecting the soil's salinity levels and nutrient content, which are critical factors influencing plant growth and ecosystem dynamics. EC measures the soil's ability to conduct electrical current, which correlates with the concentration of dissolved ions in the soil solution, including essential nutrients like potassium, calcium, and magnesium [Sustainable Agriculture Research & Education (SARE), n.d.]. High EC values often indicate saline conditions, which can inhibit plant growth and reduce crop yields, particularly in arid and semi-arid regions where water evaporation concentrates salts at the soil surface (Qadir *et al*., 2014). Conversely, excessively low EC values may indicate nutrient deficiencies or poor soil fertility, affecting overall soil productivity and plant health.

Managing EC levels involves strategies such as proper irrigation management to leach excess salts from the root zone, amending soil with organic matter to improve nutrient retention and buffering capacity, and selecting salt-tolerant crops in saline-prone areas (Ismayilov *et al.*, 2021). These practices help maintain optimal EC levels conducive to healthy plant growth and sustainable agricultural production while minimizing adverse effects of soil salinity on ecosystem functions and water quality.

C. Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) is a critical measure of soil health, indicating the soil's ability to retain and exchange cations such as calcium, magnesium, potassium and ammonium with the soil solution. It serves as a key indicator of soil fertility and nutrient retention capacity [Sustainable Agriculture Research & Education (SARE), n.d.]. Soils with high CEC are capable of holding onto essential nutrients, preventing their leaching below the root zone and ensuring availability for plant uptake over time (Brady and Weil, 2008; Parkinson and Willson, 2021). This characteristic is particularly important in agricultural systems where maintaining nutrient balance is crucial for sustaining crop yields and reducing environmental impacts.

For example, soils with low CEC may require frequent nutrient applications to meet crop demands, increasing production costs and environmental risks associated with nutrient runoff. Conversely, soils with optimal CEC levels can support healthy plant growth and minimize nutrient losses, contributing to sustainable agricultural practices (Carceles *et al.*, 2022). Management strategies to enhance CEC include adding organic matter, which improves soil structure and increases ion exchange capacity, thereby promoting nutrient availability and enhancing overall soil health (Bashir *et al.*, 2021). Monitoring CEC provides valuable insights into soil fertility management and guides decisions aimed at maximizing crop productivity, while minimizing environmental degradation.

D. Soil Organic Carbon (SOC)

Soil organic carbon (SOC) is a fundamental measure of soil health, reflecting the quantity of carbon stored within the soil organic matter, which plays a crucial role in sustaining soil fertility, microbial activity, and overall ecosystem services. SOC serves as a reservoir of nutrients and energy for soil organisms and plants, influencing soil structure, water holding capacity and nutrient cycling [Sustainable Agriculture Research & Education (SARE), n.d.]. High SOC levels indicate healthy soil conditions with active microbial communities that contribute to nutrient availability and decomposition of organic residues (Ramirez *et al.*, 2020). In contrast, depleted SOC levels can lead to degraded soil structure, reduced water retention, and increased vulnerability to erosion and nutrient leaching.

For example, agricultural practices such as intensive tillage and continuous monoculture farming often deplete SOC levels by accelerating decomposition rates and reducing organic matter input [Fiorini *et al.*, 2020]. Conversely, adopting conservation practices like cover cropping, crop rotation and reduced tillage can enhance SOC accumulation by promoting organic matter retention and stimulating microbial activity (Li *et al.*, 2020). Monitoring SOC levels over time provides valuable insights into soil health dynamics and guides management decisions aimed at restoring and maintaining soil fertility and productivity sustainably.

H. Nutrient status

The status of macronutrients and micronutrients in soil is a critical measure of soil health, directly influencing plant growth, crop yield and ecosystem sustainability. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are essential for plant physiological processes and overall productivity (Sinha and Tandon, 2020). Adequate availability of these nutrients supports robust plant growth and development, while deficiencies can lead to reduced crop yields and nutrient imbalances that compromise plant health (Marschner, 2011). For example, nitrogen deficiency can manifest in stunted growth and reduced leaf chlorophyll content, affecting photosynthesis and overall crop vigor (de Bang *et al.*, 2021). Similarly, phosphorus and potassium deficiencies can impair root development, flowering, and fruit set, impacting crop quality and yield potential (Marschner, 2011).

Micronutrients, although required in smaller quantities, are equally essential for plant growth and play crucial roles in enzyme activities and metabolic processes (Marschner, 2011). Examples include iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu), which are necessary for chlorophyll synthesis, protein metabolism, and defense against pathogens (Marschner, 2011). Soil health assessments often include analysis of both macronutrient and micronutrient levels to evaluate soil fertility and guide nutrient management strategies. Maintaining balanced nutrient levels through appropriate fertilization practices, soil amendments and crop rotation helps to sustain soil productivity and minimize environmental impacts such as nutrient runoff and leaching (Brady and Weil, 2008; Tahat *et al.*, 2020).

II. Soil Health Assessment Methods

Several assessment methods have emerged as effective tools for evaluating soil health:

1. Soil Health Cards

SHCs serve as crucial tools in modern agriculture, providing farmers with concise assessments of soil properties that facilitate informed decision-making. These cards offer a comprehensive overview of soil health indicators such as nutrient levels, pH, organic carbon content and microbial activity, essential for understanding soil fertility and productivity (Guo *et al.*, 2021; Chaudhari and Biswas, 2020). By integrating local knowledge and scientific data, SHCs enable farmers to monitor changes in soil health over time, influenced by their land management practices and environmental conditions.

SHCs recommend specific fertilizer dosages and soil amendments are tailored to the nutrient requirements of different crops grown in specific regions, thereby optimizing nutrient management practices. This personalized approach helps farmers improve crop yields sustainably while minimizing environmental impacts such as nutrient runoff and soil erosion. The SHC scheme is part of governmental initiatives aimed at enhancing agricultural productivity and promoting sustainable farming practices nationwide. By empowering farmers with practical insights into soil health management, SHCs contribute to long-term soil fertility and agricultural sustainability goals (Selvi *et al.*, 2021)

2. Solvita Soil Health Tests

The Solvita Soil Health Tests have emerged as a pivotal measure for evaluating soil health, offering insights into crucial aspects of soil biology and nutrient dynamics. Developed by Woods End Laboratories, these tests are renowned for their ability to assess soil respiration, which serves as a direct indicator of microbial activity and overall soil biological function (Woods End Laboratories; Solvita). Soil respiration, measured through carbon dioxide evolution rates, reflects the metabolic processes of soil microorganisms involved in organic matter decomposition and nutrient cycling, essential for maintaining soil fertility and ecosystem sustainability.

Research has validated the utility of Solvita Soil Health Tests across various agricultural settings by demonstrating their correlation with key soil health indicators such as soil organic carbon (SOC) and total nitrogen (TN) levels (Real Agriculture). For instance, higher soil respiration rates measured by Solvita tests often correspond to greater microbial biomass and activity, indicating healthier soils capable of efficiently cycling nutrients and supporting robust plant growth (Solvita). These tests encompass a comprehensive suite of assessments, including the determination of nitrogen availability and other microbial activity indices, which collectively provide farmers and land managers with actionable data to optimize soil management practices and enhance agricultural productivity (Guo, 2021).

By leveraging Solvita Soil Health Tests, stakeholders in agriculture can make informed decisions regarding nutrient management, soil amendments, and conservation practices aimed at improving soil health over time. This approach not only supports sustainable farming practices but also contributes to environmental stewardship by minimizing nutrient losses and promoting soil resilience against climatic stresses.

3. Haney Soil Health Test

The Haney Soil Test has emerged as a comprehensive measure of soil health, integrating biochemical and microbial assessments to provide farmers and agronomists with actionable insights into soil fertility and ecosystem resilience. Developed by Dr. Rick Haney at the USDA-ARS, this innovative test goes beyond traditional soil tests by evaluating biological indicators such as soil microbial biomass, enzyme activity, and carbon mineralization rates (USDA-ARS; Haney *et al.*, 2008). These parameters are critical for understanding soil biological activity, nutrient cycling dynamics, and overall soil health status (Gunderson, 2023).

One of the key advantages of the Haney Soil Test lies in its ability to assess the soil's capacity to supply nutrients to crops in real-time, considering both immediate availability and long-term nutrient release from organic matter (USDA-ARS). For example, the test measures soil organic carbon (SOC) and nitrogen mineralization potential, providing insights into the soil's ability to sustain plant nutrition throughout the growing season (Haney *et al.*, 2008). By incorporating microbial biomass and activity assessments, the Haney Soil Test offers a holistic view of soil health, helping farmers tailor nutrient management strategies and improve fertilizer efficiency.

Research and field validations have demonstrated the efficacy of the Haney Soil Test in predicting crop response to nutrient applications and guiding sustainable soil management practices (USDA-ARS). Studies show that soils with higher microbial activity and organic matter content, as indicated by the Haney Soil Test, exhibit improved nutrient cycling, enhanced water holding capacity and better overall productivity (Haney *et al.*, 2008). By fostering soil health through targeted amendments and management practices informed by the Haney Soil Test, farmers can optimize yields while minimizing environmental impacts such as nutrient runoff and greenhouse gas emissions.

4. Comprehensive Assessment

The Comprehensive Assessment of Soil Health (CASH), commonly referred to as the Cornell Soil Health Test, represents a pioneering approach in evaluating soil health by integrating a diverse array of indicators across physical, biological and chemical domains. Developed by the Cornell Soil Health Laboratory, CASH analyzes 15 key soil health parameters, including measures of microbial activity, nutrient cycling potential, aggregate stability and organic matter content (Nunes *et al.*, 2021; Wade *et al.*, 2022). These indicators collectively provide a comprehensive assessment of soil functionality and resilience, offering valuable insights into the overall health and productivity potential of agricultural and natural ecosystems.

For instance, CASH measures soil organic matter levels, which are crucial for enhancing soil structure, water holding capacity and nutrient availability over time (Chang *et al.*, 2022). Additionally, assessments of microbial biomass and enzyme activities in CASH provide indicators of soil biological activity and nutrient cycling efficiency, which are essential for sustaining plant health

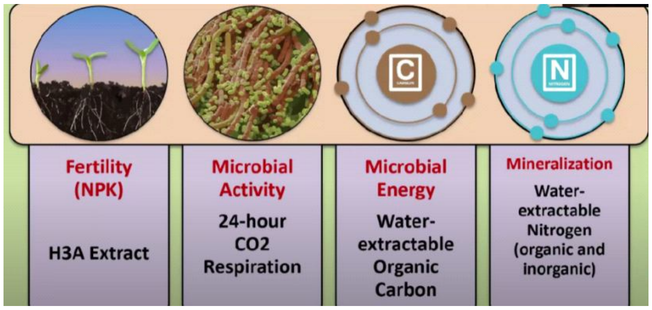

Fig. 2 : Haney Test components: The primary focus areas of the Haney test include fertility (H3A extract), microbial activity (24hr CO_2), microbial activity (Water exchangeable organic carbon, WEOC) and mineralization (water extractable nitrogen).

and productivity (SpringerLink). The test results from CASH are not only informative but also actionable, guiding farmers and land managers in making informed decisions regarding soil amendments, crop rotations and conservation practices aimed at improving soil health and long-term sustainability.

Research and practical applications of CASH have demonstrated its effectiveness in identifying soil management practices that promote optimal soil health conditions. By integrating multiple indicators into a single assessment, CASH helps stakeholders across agriculture, landscaping, and environmental sectors in optimizing soil management strategies to achieve both productivity goals and environmental stewardship.

III. Recent Advancements in Soil Health Assessment Technologies

Recent technological advancements have revolutionized soil health assessment, enhancing accuracy, efficiency and accessibility. Sensor technologies, including electromagnetic induction (EMI) and proximal soil sensing (PSS), enable high-resolution mapping of soil properties at field scales, supporting precision agriculture and site-specific management (Viscarra Rossel *et al.*, 2006; Belal *et al.*, 2021). Remote sensing techniques, such as hyperspectral imaging and Light Detection and Ranging (LiDAR), offer non-invasive approaches to monitor soil condition and vegetation dynamics, facilitating timely interventions for soil health management (Ben-Dor *et al.*, 2009).

1. Electromagnetic Induction (EMI) and Proximal Soil Sensing (PSS): Facilitate precise mapping of soil properties at field scales, supporting precision agriculture and site-specific management (Ji *et al.*, 2017). They optimize resource use efficiency and minimize environmental impacts through targeted soil management practices.
2. Remote Sensing Techniques: Hyperspectral imaging and Light Detection and Ranging (LiDAR) offer non-invasive approaches to monitor soil condition and vegetation dynamics, facilitating timely interventions for soil health management (Ben-Dor *et al.*, 2009; Abdulraheem *et al.*, 2023). These technologies provide insights into soil-plant interactions and ecosystem responses to environmental changes.

Applications of Soil Health Assessment Techniques

Soil health assessment techniques are pivotal in various agricultural and environmental domains, providing critical data that inform and enhance sustainable land management practices. These techniques are employed to evaluate the effects of diverse land use practices, such as agriculture, forestry and urban development, on soil quality and productivity. By assessing parameters like soil structure, organic matter content, and microbial activity, these techniques help identify practices that degrade soil health and those that promote its restoration and sustainability (Bhaduri *et al.*, 2022). For instance, conservation tillage and cover cropping are practices informed by soil health assessments, promoting soil carbon sequestration, water retention and biodiversity, thereby maintaining ecosystem services and enhancing resilience to climate change.

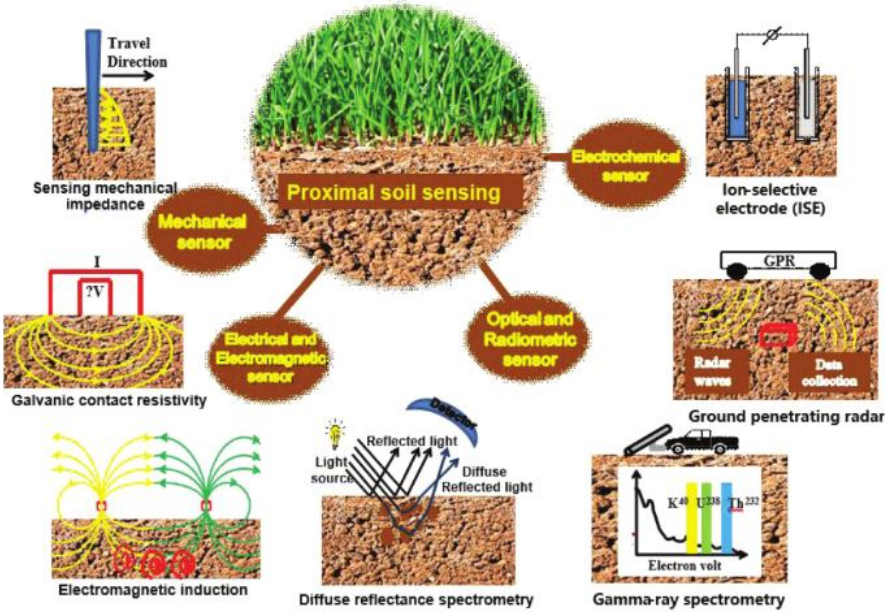

Fig. 3 : Families of Proximal soil sensing tools (Source: Adamchuk, Viacheslav *et al*, 2018).

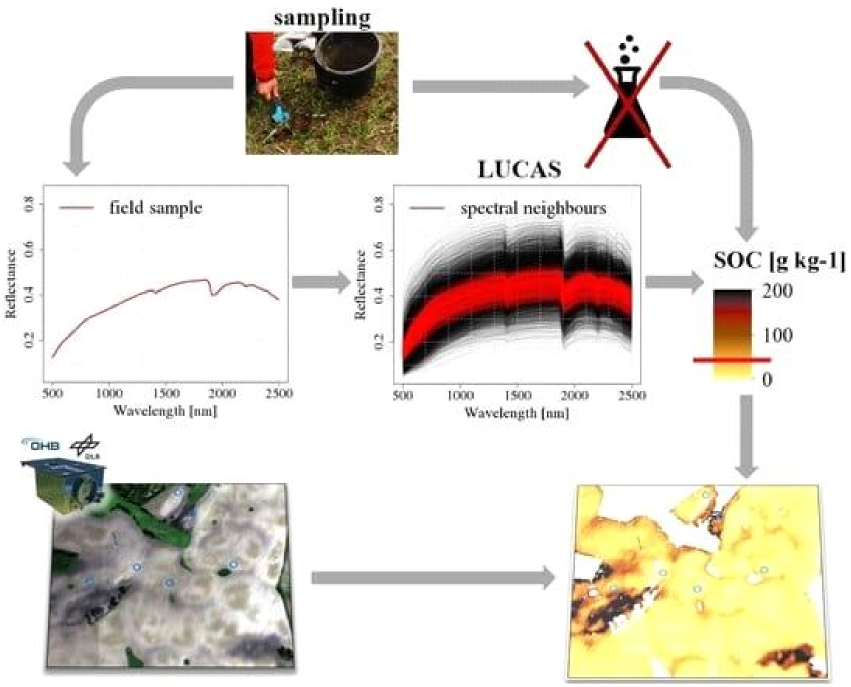

Fig. 4 : Quantification and mapping the SOC content based on fully simulated hyperspectral spaceborne images (Source: Ward *et al*, 2020).

In the realm of precision agriculture, soil health assessment techniques are revolutionizing how farmers manage their crops. The integration of real-time soil monitoring through advanced sensor networks allows for precise measurement of soil moisture, nutrient levels, and temperature. This data-driven approach enables farmers to optimize the timing and amount of irrigation and fertilization, significantly improving resource use efficiency and reducing environmental impacts, such as nutrient runoff and greenhouse gas emissions (Robertson *et al.*, 2017). For example, the use of soil moisture sensors can prevent over-irrigation, conserving water in arid regions while maintaining crop yield. Similarly, nutrient sensors can ensure that fertilizers are applied only when and where needed, minimizing the risk of pollution and promoting sustainable agricultural practices.

IV. Future Directions and Challenges

Future research in soil health assessment is poised to explore innovative methodologies and address pressing challenges to enhance the sustainability and productivity of agricultural systems. Key areas of focus include: Future research directions in soil health assessment focus on improving integration of omics technologies (*e.g.*, metagenomics, proteomics) to unravel microbial functions and interactions in soil ecosystems (Ritz *et al.*, 2009). Advances in data analytics and artificial intelligence (AI) offer opportunities to develop predictive models for soil health dynamics under changing climatic conditions (Luo *et al.*, 2020). Addressing challenges such as standardization of methodologies, interpretation of complex data outputs and integration of socio-economic factors will be crucial for advancing soil health science and promoting sustainable soil management practices globally (Helming *et al.*, 2018).

1. **Integration of Omics Technologies :** Advances in omics technologies, such as metagenomics, proteomics and transcriptomics, hold promise for unraveling microbial functions and interactions within soil ecosystems (Tiligam *et al.*, 2024). These approaches provide deeper insights into microbial communities' responses to environmental changes, nutrient cycling dynamics and their role in soil health and plant productivity.
2. **Artificial Intelligence and Data Analytics :** The application of artificial intelligence (AI) and machine learning techniques offers opportunities to develop predictive models for soil health dynamics under changing climatic conditions (Luo *et al.*, 2020). AI-driven data analytics can integrate large datasets from multiple soil health indicators to optimize agricultural management practices, improve resource use efficiency and mitigate environmental impacts.
3. **Standardization of Methodologies :** Establishing standardized protocols for soil health assessment remains a critical challenge. Harmonizing methodologies across different laboratories and regions ensures consistency and comparability of soil health data, facilitating robust scientific research and informed decision-making in agricultural management.
4. **Interpretation of Complex Data Outputs :** As soil health assessments incorporate multidimensional indicators, interpreting complex data outputs becomes increasingly challenging. Developing frameworks and tools for data interpretation and visualization helps stakeholders —from farmers to policymakers—derive actionable insights and implement effective soil management strategies.
5. **Integration of Socio-economic Factors :** Recognizing the socio-economic dimensions of

soil health is essential for promoting sustainable land management practices. Understanding how socio-economic factors influence soil management decisions and agricultural practices enables the development of inclusive policies and strategies that support both environmental sustainability and livelihoods.

Addressing these future directions requires collaborative efforts among researchers, practitioners, policymakers and stakeholders across disciplines. By overcoming these challenges and leveraging technological advancements, the scientific community can advance soil health science, enhance agricultural resilience, and ensure food security in a changing climate.

Conclusion

In conclusion, this paper has explored new ways to assess soil health for better land management. We've looked at various methods that measure physical, chemical and biological aspects of soil to understand its overall health. A standout aspect of this research is how it integrates advanced technologies like electromagnetic induction and remote sensing. These tools help map soil properties accurately, which is crucial for managing farmland effectively. The study highlights the importance of biological indicators such as microbes and enzymes in assessing soil fertility. These indicators show us how nutrients move through the soil and how different organisms interact to support plant growth. Looking forward, future research could use new technologies and artificial intelligence to predict changes in soil health. It's important to standardize methods and make sense of complex data to improve how we manage soil health and support sustainable farming practices worldwide. In summary, collaboration among scientists, farmers and policymakers is key to improving soil health and ensuring food security in a changing climate. By using new technologies and working together, we can protect our soils and sustainably produce food for the future.

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