



Advances in Soil Health Monitoring: A Review of Digital and Sensor-Based Tools

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ABSTRACT

Soil health is a critical factor for ensuring sustainable agricultural productivity and environmental balance. Over the past decade, the rapid advancement of digital tools and sensor-based technologies has revolutionised the way soil health is monitored and managed. Traditional methods, which often involved labour-intensive manual sampling and limited spatial coverage, have been gradually replaced by digital platforms and real-time sensor systems that offer precise, continuous, and scalable data collection. These innovations, ranging from IoT-based sensors, drones, and satellite imagery to advanced machine learning algorithms, are now enabling farmers, researchers, and policymakers to monitor soil conditions with unprecedented accuracy and efficiency. This review article explores the evolution of soil health monitoring tools, focusing on the integration of digital and sensor-based technologies. It examines the types of tools currently available, their applications in precision agriculture, and the challenges and limitations faced in their

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implementation. Additionally, the article highlights the role of artificial intelligence and machine learning in transforming data analysis and predictive modelling for soil health. Finally, the article discusses the future potential of these technologies, exploring opportunities for scaling them globally and the role of policy in supporting their widespread adoption. As digital and sensor-based tools continue to advance, they promise to play a pivotal role in achieving agricultural sustainability and improving soil management practices worldwide.

Keywords: *Soil health; digital tools; sensor technology; precision agriculture; sustainable agriculture.*

1. INTRODUCTION

1.1 Importance of Soil Health

Soil health refers to the capacity of the soil to function as a living ecosystem that supports plant growth, maintains biodiversity, and performs critical ecosystem services such as carbon sequestration and water filtration. Soil is often called the “lungs of the Earth” due to its vital role in sustaining life. However, it faces unprecedented pressure due to human activities like industrial agriculture, deforestation, and urbanisation. Degrading soil health can lead to reduced agricultural productivity, loss of biodiversity, and increased susceptibility to environmental issues such as erosion, desertification, and climate change (Dubey et al., 2024).

In agricultural systems, soil health directly impacts crop yields, pest resistance, and the quality of the produce. Healthy soils contain a balanced mix of organic matter, nutrients, and microorganisms that support plant growth, while also storing carbon and filtering water. A deteriorating soil environment, on the other hand, can result in poor soil structure, erosion, and loss of nutrients, ultimately reducing soil fertility and making crops more vulnerable to disease and climate variations (Gebresenb et al., 2023).

Maintaining soil health is therefore crucial for achieving long-term agricultural sustainability, food security, and environmental preservation. Efforts to monitor and manage soil health can help farmers adopt more sustainable practices, reduce the reliance on chemical fertilisers, and implement appropriate soil conservation techniques to optimise productivity (Silva et al., 2023).

1.2 Traditional Soil Monitoring Techniques

Historically, soil health has been monitored through traditional techniques such as visual

inspections, manual sampling, and laboratory analysis. These methods, while effective in some contexts, come with notable limitations. Soil sampling involves collecting samples from different locations on a farm, which are then sent to laboratories for analysis. This process can be time-consuming and expensive, often requiring specialized knowledge and equipment to interpret the results accurately. Furthermore, traditional methods only provide a snapshot of soil health at a specific time and location, limiting their ability to track real-time changes in soil conditions (de Paul Obade et al., 2021).

Other traditional monitoring approaches include visual inspection of plant health, which provides indirect insights into soil conditions. However, such methods can be subjective and dependent on the observer's experience. Additionally, they fail to provide a comprehensive understanding of the soil's physical, chemical, and biological properties, leaving many potential issues unaddressed (Aarif et al., 2025).

While traditional soil monitoring methods are still in use today, they are increasingly being complemented or replaced by more advanced tools that provide continuous, real-time data and cover larger spatial areas. This transition is especially significant in the context of modern agriculture, where precision and efficiency are key to maximising yields while minimising environmental impact (Singh et al., 2022).

1.3 Emergence of Digital and Sensor-Based Tools

Over the last two decades, the development of digital tools and sensor technologies has transformed soil health monitoring. The rise of the Internet of Things (IoT), satellite-based technologies, drones, and machine learning has enabled farmers, researchers, and agricultural professionals to gather data in real-time, making it easier to monitor and manage soil health at a large scale (Getahun et al., 2024).

Digital platforms such as farm management software now integrate data from multiple sources, including weather forecasts, soil sensors, and crop management tools, to provide farmers with actionable insights about their soil conditions. These platforms can track and analyze data continuously, helping users identify issues early, predict soil changes, and make informed decisions (Diaz-Gonzalez et al., 2022).

Sensor-based technologies have been particularly instrumental in soil health monitoring. By embedding sensors in the soil or using remote sensing technologies like drones and satellites, it is now possible to measure key soil properties such as moisture, pH, temperature, and nutrient content with high precision. These sensors provide continuous, real-time data that can be easily accessed through mobile devices or computer systems. This allows farmers to adjust their practices dynamically, improving soil management without waiting for laboratory results (Silva et al., 2023).

The adoption of digital and sensor-based tools represents a paradigm shift from conventional soil monitoring methods, offering several advantages, including:

- **Real-time data:** Continuous monitoring allows for the early detection of changes in soil conditions, enabling timely interventions (Gebresenb et al., 2023).
- **Higher accuracy:** Sensors and digital tools can provide precise measurements and mitigate human errors associated with manual sampling (de Paul Obade et al., 2021).
- **Scalability:** Digital tools can be applied across large-scale agricultural systems, making them suitable for both smallholder farms and industrial-scale operations (Singh et al., 2022).
- **Cost-effectiveness:** Though initial investments may be high, digital tools and sensors can reduce the long-term costs associated with traditional soil testing by eliminating the need for frequent lab analysis and improving overall efficiency (Aarif et al., 2025).

The potential of digital tools and sensors to improve soil health management is vast, offering solutions to the challenges faced by conventional soil monitoring methods. These advancements not only enhance precision but also enable farmers to adopt more sustainable

and data-driven approaches to soil management (Silva et al., 2023).

2. DIGITAL TOOLS FOR SOIL HEALTH MONITORING

2.1 Types of Digital Tools

In the realm of soil health monitoring, digital tools play a pivotal role in facilitating accurate, real-time data collection and analysis. These tools integrate various technologies to monitor, analyse, and visualise soil conditions, providing farmers and land managers with actionable insights to optimise soil health and productivity. The key types of digital tools include:

- **Farm Management Software:** Digital platforms like precision agriculture software are integral to soil health monitoring. These software solutions aggregate data from multiple sources, such as soil sensors, weather stations, and satellite imagery, to provide real-time insights into soil conditions. They enable farmers to monitor soil moisture levels, nutrient content, pH, and temperature across various fields or regions. Popular platforms include Ag Leader and John Deere Operations Centre, which offer features like variable rate application (VRA) for fertilisers, irrigation management, and crop health monitoring (Vasisht et al., 2017).
- **Remote Sensing Technologies:** Remote sensing plays an essential role in soil health monitoring by providing data from a distance, often through satellites, drones, or airborne sensors. Remote sensing technologies use various spectral bands to assess soil properties like moisture content, organic matter, and vegetation health. Satellite systems like Sentinel-2 and commercial drones equipped with hyperspectral or multispectral cameras offer valuable insights into soil health on a large scale. These systems can track soil erosion, fertility, and moisture across vast areas, making them ideal for monitoring soil health in diverse and remote locations (Meivel & Maheswari, 2021).
- **Geographic Information Systems (GIS):** GIS technologies are powerful tools for managing spatial data related to soil health. GIS allows farmers to map out soil characteristics across large tracts of land, visualise the distribution of soil properties,

and analyse the relationships between soil conditions and crop yields. This technology can be integrated with remote sensing data to create detailed soil health maps, enabling targeted management practices. GIS tools also help farmers understand variations in soil properties within a field, enabling precision farming practices that optimise input usage, reduce waste, and enhance soil quality (Fuentes-Peñailillo et al., 2024).

- **Mobile Apps:** A growing number of mobile applications are available that connect farmers with soil health data and insights directly on their smartphones or tablets. These apps, such as SoilCares and AgriWebb, allow users to monitor soil conditions, track field activities, and access recommendations based on soil analysis. Many of these apps integrate with other digital tools, such as soil sensors or drones, and offer features like soil sampling, fertiliser recommendations, and irrigation scheduling, making them accessible and user-friendly for farmers in both developed and developing regions (Almalki et al., 2021).

2.2 Data Collection Methods

The effectiveness of digital tools depends heavily on the data collection methods employed. Several technologies are used for the collection of soil health data, ensuring that the gathered information is accurate, timely, and comprehensive:

- **IoT-Based Sensors:** The Internet of Things (IoT) is a key enabler in soil health monitoring. Sensors are embedded within the soil to continuously measure parameters like moisture, pH, temperature, and electrical conductivity (EC). These sensors provide real-time data, which can be transmitted wirelessly to cloud-based platforms for analysis and decision-making. Examples of IoT sensors include Decagon Devices, which offers soil moisture and temperature sensors that can integrate with farm management software for automated irrigation control (Ullo & Sinha, 2021).
- **Drones and UAVs (Unmanned Aerial Vehicles):** Drones are increasingly used for soil health monitoring due to their ability to capture high-resolution imagery and provide multispectral or hyperspectral

data. UAVs equipped with remote sensing technology can cover large agricultural fields quickly and efficiently, enabling farmers to monitor changes in soil moisture, temperature, and vegetation health. Drones can also help identify areas of soil degradation, compaction, or erosion that may need special attention (Zhao et al., 2023).

- **Satellite Imagery:** Satellites orbiting the Earth are a valuable source of data for monitoring large-scale soil health. Satellite platforms like NASA's Landsat or the European Space Agency's Sentinel provide regularly updated imagery that can be analysed to assess soil conditions. These satellites capture data across various bands, allowing for detailed assessments of soil properties such as moisture content and organic matter, which are critical indicators of soil health (Petkovic et al., 2017).
- **Soil Sampling and Lab Analysis Integration:** While digital tools offer real-time monitoring, traditional soil sampling and laboratory analysis still play an important role in obtaining baseline data. Digital tools often integrate with lab results to offer a comprehensive view of soil health. Soil samples can be taken periodically and analysed in a laboratory to measure nutrient levels, texture, and organic content. This data is then uploaded into digital platforms to enhance the predictive models that guide farming decisions (Cadavid et al., 2018).

2.3 Case Studies of Digital Tools in Use

Digital tools have already demonstrated significant success in improving soil health management across the globe. A few notable case studies include:

- **Precision Agriculture in the United States:** In the U.S., precision agriculture technologies have revolutionised soil health monitoring. By using digital platforms like Climate FieldView, farmers can monitor soil moisture, track nutrient levels, and adjust irrigation and fertilisation practices in real-time. These tools have enabled farmers to optimise their soil management practices, improving yield and reducing input costs. One notable case involves a farmer in the Midwest who used real-time soil moisture data from IoT

sensors to reduce water usage and increase crop yield by 25% (Vasisht et al., 2017).

- **Sustainable Farming in Kenya:** In Kenya, digital tools are being utilised to monitor soil health in smallholder farming systems. Mobile apps like M-Farm and SoilCares help farmers assess soil health by providing mobile soil testing services. By analysing the soil's nutrient composition, these apps guide farmers on the right amount of fertilisers to apply, reducing the overuse of chemical inputs and improving soil fertility. This approach not only boosts crop productivity but also contributes to more sustainable agricultural practices (Almalki et al., 2021).
- **Soil Monitoring with Drones in Australia:** In Australia, the use of drones equipped with multispectral sensors has been highly effective in monitoring soil health across large agricultural properties. These drones capture data on vegetation health, soil erosion, and moisture content, providing farmers with the information they need to make informed decisions about irrigation and crop management. A farm in Queensland successfully integrated drone technology with soil moisture sensors to improve water efficiency and reduce fertiliser usage (Meivel & Maheswari, 2021).

2.4 Advantages of Digital Tools in Soil Health Monitoring

The integration of digital tools in soil health monitoring offers numerous advantages:

- **Real-Time Data:** Digital tools provide continuous, real-time monitoring, enabling early detection of soil health issues and timely interventions.
- **Increased Accuracy:** Automated data collection reduces human error, offering more accurate insights into soil conditions.
- **Scalability:** Digital tools can be used in small-scale farms or large agricultural operations, offering flexibility for various farming systems.
- **Cost Efficiency:** Although the initial investment may be high, digital tools can reduce costs in the long run by optimising input usage, improving yield, and reducing reliance on traditional labour-intensive soil analysis.

2.5 Challenges in the Adoption of Digital Tools

Despite the significant benefits, the adoption of digital tools in soil health monitoring also faces several challenges:

- **High Initial Costs:** The cost of advanced technologies, such as soil sensors and drones, can be prohibitive for smallholder farmers, particularly in developing regions.
- **Data Integration Issues:** Integrating data from various sources (e.g., sensors, drones, and satellites) into a cohesive and usable format can be complex.
- **Technical Expertise:** Farmers need proper training to use these tools effectively, and there may be a lack of technical support in rural areas (Ullo & Sinha, 2021).

3. SENSOR-BASED TOOLS IN SOIL HEALTH MONITORING

3.1 Types of Sensors for Soil Health Monitoring

Sensor-based tools have become indispensable in soil health management. These sensors provide real-time data on critical soil properties, enabling precise and timely interventions to optimise soil conditions for agricultural success. Various types of sensors are used in soil health monitoring, each designed to measure specific parameters:

- **Soil Moisture Sensors:** Soil moisture is one of the most critical parameters for soil health. Sensors that measure soil moisture help farmers determine the irrigation needs of their crops and prevent over- or under-watering. These sensors can measure the water content in the soil at various depths, providing a comprehensive understanding of soil moisture distribution. Common types of soil moisture sensors include capacitive, resistive, and time-domain reflectometry (TDR) sensors. These sensors are integrated into farm management systems to provide irrigation recommendations and ensure water conservation (Chen et al., 2025).
- **Temperature Sensors:** Soil temperature affects plant growth, microbial activity, and nutrient availability. Temperature sensors placed in the soil can track temperature

fluctuations over time, enabling farmers to optimise planting times, adjust irrigation schedules, and monitor plant health. Soil temperature also plays a role in determining the effectiveness of fertilisers and pesticides. High or low temperatures can impact nutrient uptake, root growth, and soil microbial communities (Hedley, 2015).

- **pH Sensors:** The pH level of the soil directly influences the availability of essential nutrients to plants. pH sensors are used to monitor soil acidity or alkalinity and guide farmers in managing soil amendments such as lime or sulfur to adjust the pH. Maintaining a balanced pH is crucial for optimal soil health, as it impacts nutrient absorption, microbial activity, and overall soil fertility (Najdenko et al., 2024).
- **Nutrient Sensors:** Soil nutrient sensors measure key nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients like calcium, magnesium, and sulfur. These sensors provide real-time data on soil nutrient levels, helping farmers apply fertilisers more effectively and in a targeted manner. Nutrient sensors are especially useful in precision agriculture, where farmers aim to optimise input use while minimising environmental impact (Singh et al., 2023).
- **Electrical Conductivity (EC) Sensors:** Electrical conductivity sensors measure the ion concentration in the soil, providing valuable insights into soil salinity and nutrient availability. High salinity levels can affect crop growth, while low salinity may indicate nutrient deficiencies. By monitoring EC, farmers can take proactive measures to manage soil salinity, enhance nutrient uptake, and improve crop yield (Raza et al., 2023).

3.2 How Sensors Work

The working principles behind soil sensors vary based on the type of sensor used. Most sensors function by detecting changes in the physical or chemical properties of the soil and converting these changes into measurable signals. Below are the primary principles of operation for standard soil sensors:

- **Capacitive Sensors:** These sensors measure the soil's dielectric constant, which changes with moisture content. By detecting the change in capacitance, they

can accurately determine the amount of water present in the soil.

- **Resistive Sensors:** These sensors measure the electrical resistance between two probes inserted into the soil. The resistance is inversely proportional to the soil moisture content; as moisture levels increase, the resistance decreases.
- **TDR Sensors (Time Domain Reflectometry):** These sensors use the time it takes for a signal to travel through the soil to determine moisture levels. The speed of the signal changes depending on the water content of the soil, allowing for precise moisture measurement.
- **pH Sensors:** pH sensors work by measuring the hydrogen ion concentration in the soil solution. Electrodes in the sensor detect the ions, which are then converted into a pH value.
- **Nutrient and EC Sensors:** Nutrient sensors typically use ion-selective electrodes or optical sensors to detect nutrient levels in the soil. For EC sensors, electrical conductivity is measured using two electrodes placed in the soil, and the resulting data is used to determine ion concentration and salinity.

Most modern soil sensors are equipped with wireless communication systems, allowing them to transmit data to cloud-based platforms or mobile apps. This data can then be analysed in real-time, providing farmers with actionable insights and recommendations for soil management (Sharma & Tomar, 2025).

3.3 Real-Time Monitoring and Data Analysis

The primary advantage of sensor-based tools is their ability to provide real-time data on various soil parameters. Continuous monitoring allows for the early detection of changes in soil health, enabling farmers to take immediate action. For example, if soil moisture levels fall below optimal ranges, irrigation can be adjusted, and if nutrient levels are too low, targeted fertilisation can be applied.

Sensor data can also be integrated with farm management software, allowing for automated decision-making and precision farming. By analysing the data from multiple sensors, farmers can create detailed soil health profiles that help them manage resources more efficiently. For example:

- **Soil Moisture Management:** Based on real-time moisture data, irrigation schedules can be optimised, reducing water waste and improving crop health.
- **Nutrient Optimisation:** Nutrient sensors help farmers determine when and where to apply fertilisers, ensuring that crops receive the right amount of nutrients at the right time.
- **Microclimate Monitoring:** Temperature and pH sensors can help monitor microclimates within a field, allowing farmers to adapt their practices based on localised conditions.

In addition to improving resource efficiency, real-time data analysis helps reduce operational costs, improve yield, and enhance soil fertility by minimising overuse of water, fertilisers, and pesticides (Zhao et al., 2023).

3.4 Case Studies of Sensor Applications

- **Smart Irrigation Systems in California:** In California, sensor-based irrigation systems have been deployed to monitor soil moisture levels and adjust irrigation schedules accordingly. The CropX system, which integrates soil moisture sensors with a cloud-based platform, provides farmers with real-time data on soil conditions. By using this data, farmers can reduce water usage by up to 30%, optimising both crop yield and water conservation. The system has been particularly effective in water-scarce regions, where managing irrigation is critical for sustainability (Chen et al., 2025).
- **Nutrient Management in Brazil:** In Brazil, precision agriculture technologies have been used to monitor nutrient levels in soil across large soybean farms. By deploying soil nutrient sensors and integrating them with farm management software, farmers can precisely manage fertiliser applications. This approach has reduced fertiliser costs by up to 20% and minimised the environmental impact of excessive fertiliser use, leading to more sustainable farming practices (Raza et al., 2023).
- **Salinity Monitoring in Australia:** In Australia, salinity sensors have been used to monitor soil salinity in irrigation-dependent areas. The data from these sensors is used to adjust irrigation

practices and avoid salinity buildup, which can degrade soil quality and reduce crop productivity. The system has proven effective in managing soil health, ensuring that salinity levels are kept within acceptable ranges to prevent crop damage (Najdenko et al. 2024).

3.5 Advantages of Sensor-Based Tools

The integration of sensor-based tools in soil health monitoring offers numerous advantages:

- **Precision:** Sensors offer accurate, continuous data on soil conditions, ensuring that interventions are tailored to the needs of the soil.
- **Real-Time Monitoring:** With sensors providing constant feedback, farmers can make immediate adjustments to their practices, improving productivity and reducing waste.
- **Automation:** Sensor-based systems can automate key functions, such as irrigation and fertilisation, reducing the need for manual labour and minimising human error.
- **Cost Efficiency:** Over time, the use of sensors can lead to reduced input costs (e.g., water and fertilisers) and improved crop yields, providing a positive return on investment.
- **Sustainability:** By using sensors to optimise input use and reduce waste, farmers can practice more sustainable agriculture, minimising their environmental footprint.

3.6 Challenges in Sensor-Based Monitoring

Despite their many benefits, sensor-based tools face several challenges:

- **High Initial Costs:** The upfront cost of purchasing and installing sensors can be significant, which may be a barrier for smallholder farmers.
- **Calibration and Maintenance:** Sensors need regular calibration and maintenance to ensure accurate data. In some regions, access to technical support may be limited.
- **Data Management:** Large volumes of sensor data need to be appropriately stored, analysed, and interpreted.

Managing this data can be challenging, particularly for farmers with limited technical expertise.

- **Durability:** Sensors must withstand harsh environmental conditions, such as extreme temperatures, moisture, and soil abrasiveness. In some cases, sensor failure can lead to inaccurate data (Hedley, 2015).

4. INTEGRATION OF DIGITAL AND SENSOR-BASED TOOLS

4.1 Complementary Roles of Digital Tools and Sensors

In modern soil health monitoring, digital tools and sensor-based technologies work synergistically to provide a comprehensive, real-time view of soil conditions. Each type of tool whether digital platforms, sensors, or remote sensing technologies brings unique advantages to the table, but their true power emerges when they are integrated into a unified system.

- **Digital Platforms:** These are designed to process, analyse, and visualise data collected from various sources. They serve as the interface where users (farmers, agronomists, and researchers) can access insights and make decisions. These platforms can integrate data from IoT sensors (measuring soil moisture, pH, etc.), remote sensing technologies (drones, satellite imagery), and manual soil tests to create an integrated management dashboard. This integration enables users to see the overall health of their soil, track changes over time, and optimise farming practices (CropX Technologies, 2022).
- **Sensors:** The sensors provide the actual data points on soil health parameters (e.g., moisture, temperature, nutrient levels). They are the 'eyes and ears' on the ground, collecting real-time data from the soil. Sensors can be placed at various depths and locations within a field, delivering granular insights that help farmers manage variability within the soil at a very local level. This technology enables efficient management of field variability, ensuring proper irrigation, fertilisation, and crop protection (AgroCares, n.d.).

When integrated, digital platforms provide the framework for aggregating and analysing sensor data, turning it into actionable insights. For

example, soil moisture sensors feed data into a farm management system, which then uses weather data and crop-specific requirements to recommend irrigation schedules (FarmTRX, 2024). This complementary interaction allows for more precise, efficient, and data-driven soil management practices.

4.2 Technological Synergy in Soil Health Management

The synergy between digital tools and sensors enables farmers to shift from reactive to proactive soil management. Instead of waiting for soil issues to manifest (e.g., nutrient deficiencies, water stress), integrated systems allow for predictive management based on real-time data and historical trends. This ensures that farmers can make adjustments before problems affect crop yield or soil health.

For example:

- **Real-time Monitoring and Adjustment:** Sensors can detect changes in soil moisture, temperature, or nutrient levels, and digital platforms can automatically adjust irrigation or fertilisation schedules based on this data (Ranch Systems, Inc., 2020). This leads to more efficient use of water and fertilisers, reducing waste and costs while improving soil health.
- **Precision in Field Management:** Data collected by sensors allows farmers to map their fields' varying soil conditions (e.g., soil texture, nutrient content) and adjust farming practices according to localised requirements. These insights help farmers optimise inputs, like fertiliser and water, based on precise field conditions, thus avoiding overuse and improving crop yields (John Deere, 2024).

This technological synergy promotes precision agriculture, a farming method that uses data-driven insights to optimise every aspect of farming, from planting to irrigation to harvesting. By integrating sensors with digital tools, farmers can achieve higher yields, lower input costs, and more sustainable practices

4.3 Challenges in Integration

While the integration of digital tools and sensor-based technologies offers numerous benefits, it also presents several challenges, both technical

and logistical. These challenges must be addressed to realise the potential of integrated soil health management systems fully.

- **Data Compatibility:** Integrating data from different sources such as sensors, drones, satellites, and manual soil tests into a single platform can be complex. Data formats may vary, and sensors from different manufacturers may not be fully compatible with each other. Ensuring that all data sources can work together seamlessly is a critical step in building an effective integrated system.
- **Cost of Integration:** The initial investment in both sensor technology and digital platforms can be high, particularly for smallholder farmers. In addition to purchasing hardware (sensors, drones, etc.), farmers need to invest in software, connectivity infrastructure, and sometimes even training. For large-scale operations, these costs can be justified by the potential return on investment, but for smaller operations, these costs might be prohibitive (Vasantdada Sugar Institute, 2025).
- **Complexity and Usability:** Even when digital tools and sensors are integrated, the system's complexity may be overwhelming for some farmers. The software may require technical expertise to operate, and the large volume of data generated can be challenging to interpret without proper knowledge. There is also a need for user-friendly interfaces that can simplify the data presentation and make it actionable for farmers with limited technical skills.
- **Data Privacy and Security:** With the growing use of cloud-based platforms for storing and analysing sensor data, data privacy and security have become significant concerns. Farmers need assurance that their data will not be misused or exposed to unauthorised access. Securing this data, especially when it involves sensitive farm management practices, is crucial for building trust and ensuring long-term adoption (CropX Technologies, 2022).

4.4 Case Studies of Integrated Systems

To highlight the potential of integrated digital and sensor-based tools, here are some case studies where these technologies have been successfully implemented:

- **Farm Management System in the U.S.:** In the U.S., John Deere's Operations Center integrates data from various IoT sensors, GPS, and remote sensing technologies to provide farmers with a comprehensive soil health management tool. This integrated system helps farmers track soil moisture levels, nutrient deficiencies, and pH variations in real time. For instance, in a corn field, soil moisture sensors track the water content and feed this data to the system, which adjusts irrigation schedules to optimise water use (FarmTRX, 2024). This integrated system has helped farmers reduce water usage by 20-30% and increase crop yield by 10-15%.
- **Integrated Precision Farming in India:** In India, a precision farming system was implemented in a large-scale sugarcane farm. This system used a combination of satellite imagery, drone-based sensors, and soil moisture sensors to monitor soil health and optimise irrigation. The system integrated all the collected data into a farm management platform, which provided real-time insights and recommended optimal irrigation schedules (John Deere, 2024). The integration of data resulted in a 25% reduction in water use and a 12% increase in crop yield.
- **Sustainable Farming in Africa:** In several African countries, sensor-based tools are integrated with mobile platforms to assist smallholder farmers in managing soil health. For example, farmers in Kenya use mobile apps like SoilCares to conduct soil tests and get recommendations on how to improve their soil health. The app integrates data from both manual soil tests and real-time sensor inputs (such as soil moisture) to provide localised recommendations for irrigation, fertilisation, and crop management (AgroCares, n.d.).

4.5 Advantages of Integration

The integration of digital tools in soil health monitoring offers numerous advantages for farmers:

- **Enhanced Efficiency:** By integrating sensors with digital tools, farmers can automate several aspects of farm management, including irrigation, fertilisation, and pest control, resulting in

higher efficiency and reduced labour costs.

- **Timely Decisions:** Real-time data from sensors enables farmers to make informed decisions based on the most current soil conditions. This leads to timely interventions, such as adjusting irrigation or applying fertilisers before problems arise.
- **Sustainability:** The ability to monitor and manage soil conditions more precisely reduces the risk of overusing inputs, such as water, fertilisers, and pesticides, which is crucial for both environmental sustainability and cost reduction.
- **Data-Driven Insights:** The integration of diverse data sources allows farmers to gain a deeper understanding of soil health. This enables better decision-making, with the potential for higher yields and healthier soils.

5. ADVANCES IN MACHINE LEARNING AND AI FOR SOIL HEALTH MONITORING

5.1 Role of Machine Learning and AI

Machine learning (ML) and artificial intelligence (AI) are transforming the way we approach soil health monitoring. By leveraging advanced algorithms and vast amounts of data, AI and ML can detect patterns and make predictions that are otherwise challenging for humans to identify. These technologies can process data collected from various sources, such as sensors, satellite imagery, and environmental data, to make accurate predictions about soil health, crop needs, and future soil conditions (Schweng et al., 2026).

- **Predictive Analytics:** ML algorithms can be trained on historical data to predict soil health outcomes based on current conditions. For instance, predictive models can estimate nutrient levels, the likelihood of soil erosion, or the best planting times, allowing farmers to make more informed decisions and optimise their soil management practices (Vhatkar, 2025).
- **Pattern Recognition:** AI excels in identifying patterns in large datasets. For soil health, this could involve recognizing correlations between soil moisture levels, temperature, and crop growth patterns. These insights allow farmers to anticipate

soil issues before they impact yields and crop quality (Awais & Khan, 2023).

By incorporating machine learning, farmers can move beyond reactive management to predictive soil health management, optimising their practices for the best possible outcomes.

5.2 Predictive Models

Predictive models powered by AI and ML algorithms use data from various sources such as sensors, weather forecasts, and soil tests to anticipate soil conditions and crop health. These models are valuable tools for precision agriculture, as they allow farmers to take proactive measures to enhance soil health and improve crop productivity (Pandey et al., 2025).

- **Soil Moisture Predictions:** AI-based models can analyse historical weather patterns, current moisture levels, and crop requirements to predict future soil moisture conditions. This helps farmers adjust irrigation schedules in advance, ensuring optimal moisture levels and preventing water wastage (Chaudhary, 2025).
- **Nutrient Availability:** Machine learning can predict nutrient dynamics in the soil by analysing historical nutrient data, weather conditions, and other environmental factors. These models can recommend the precise amount of fertilisers or soil amendments required to optimise soil health, reducing the risk of over- or under-fertilising (Rosca, 2025).
- **Disease and Pest Prediction:** AI models can also predict potential pest and disease outbreaks based on soil health and environmental factors. By analysing soil moisture, temperature, and pest population data, AI systems can provide early warnings and suggest appropriate interventions, reducing crop losses and minimising pesticide use (Folorunso, et al., 2023).

These predictive models are becoming increasingly accurate and are being integrated into farm management platforms to offer farmers timely insights and recommendations based on real-time data.

5.3 AI in Soil Health Data Analysis

AI-driven data analysis has the potential to revolutionise soil health monitoring by

automating the interpretation of complex datasets. Traditional soil testing methods often require manual analysis and interpretation, which can be time-consuming and prone to human error. AI and ML algorithms, on the other hand, can rapidly process large volumes of data and identify patterns that may be invisible to the human eye (Chaudhary, 2025).

- **Automated Data Processing:** AI can automate the processing of data from various soil sensors and remote sensing technologies. For instance, AI can analyse data from moisture and temperature sensors, satellite imagery, and crop performance metrics to create an accurate picture of soil health across a field or farm (Hossen & Diwaka, 2021).
- **Decision Support Systems:** AI-powered decision support systems can provide farmers with actionable recommendations based on real-time data analysis. These systems can suggest the best times for planting, fertilising, or harvesting, as well as optimise irrigation schedules to reduce water consumption and improve soil health (Vhatkar, 2025).

Through automation and real-time analysis, AI can significantly enhance soil health management by providing more accurate insights and recommendations than traditional methods.

5.4 Future of AI in Soil Health

The future of AI in soil health monitoring holds immense promise. As AI and machine learning technologies continue to evolve, we can expect more sophisticated tools that can predict soil health with greater accuracy and integrate seamlessly with other farming technologies (Schweng et al., 2026).

- **AI-Driven Soil Health Mapping:** Advances in AI will enable more precise and detailed soil health maps. AI can analyse data from multiple sources such as drone imagery, soil sensors, and satellite data to create comprehensive maps that show variations in soil health across a field. This will enable farmers to make more localised and targeted decisions, improving soil management at the micro-level (Naimi & Zhang, 2022).
- **Integration with Autonomous Farming Systems:** AI will likely play a key role in

autonomous farming systems that use robots, drones, and automated machinery to manage soil health. These systems will rely on AI to make real-time decisions about soil management, such as adjusting irrigation, applying fertilisers, or detecting soil compaction, all without human intervention (Pandey et al., 2025).

- **Enhanced Data Fusion:** The integration of diverse data sources will become even more sophisticated. AI will fuse data from multiple sensors, weather stations, and farm management systems to provide a holistic view of soil health, crop performance, and environmental conditions, enabling more innovative, data-driven farming practices (Awais & Khan, 2023).

As these AI technologies continue to evolve, they will become essential tools for soil health monitoring and management, helping farmers optimise practices, reduce environmental impacts, and improve productivity.

5.5 Case Studies of AI in Soil Health Monitoring

AI-powered soil health monitoring systems are already being used in various agricultural settings to improve soil management practices. Here are a few examples:

- **AI-Based Irrigation Systems in Israel:** In Israel, AI-powered irrigation systems are used to optimise water use in arid regions. The system collects data from soil moisture sensors, weather forecasts, and crop needs, and uses machine learning to predict irrigation requirements. By adjusting irrigation schedules based on these predictions, the system ensures that crops receive the right amount of water at the right time, preventing water wastage and improving soil health (Chaudhary, 2025).
- **Precision Farming in the Netherlands:** In the Netherlands, AI is being used to improve the management of organic soils in greenhouse farming. By analysing data from soil sensors, temperature sensors, and crop performance data, AI systems can recommend optimal fertilisation schedules and adjust greenhouse climate conditions to promote healthy soil. These AI-driven recommendations have helped farmers reduce fertiliser usage while

maintaining high crop yields (Rosca, 2025).

- **Soil Health Monitoring in India:** In India, AI-powered soil health monitoring systems are being implemented in large-scale farming operations. These systems use machine learning algorithms to analyse soil nutrient levels, moisture content, and temperature data collected from IoT sensors placed throughout the fields. The AI system provides farmers with real-time insights into soil health and recommends adjustments to improve soil fertility and enhance crop production (Naimi & Zhang, 2022).

5.6 Advantages of AI in Soil Health Monitoring

The integration of AI in soil health monitoring offers several advantages:

- **Increased Precision:** AI algorithms can process and analyze vast amounts of soil data with greater accuracy than traditional methods, leading to more precise soil health recommendations (Schweng et al., 2026).
- **Cost Efficiency:** AI can help reduce input costs by optimizing the use of water, fertilizers, and pesticides, leading to cost savings for farmers (Awais & Khan, 2023).
- **Sustainability:** AI-powered systems help minimize the environmental impact of farming by promoting more efficient use of resources and reducing the over-application of fertilizers and pesticides (Pandey et al., 2025).
- **Real-Time Decision-Making:** AI enables farmers to make timely decisions based on real-time data, leading to more responsive and proactive soil management (Vhatkar, 2025).

5.7 Challenges in AI Implementation

Despite the benefits, implementing AI in soil health monitoring comes with challenges:

- **Data Quality:** AI systems rely on high-quality data to make accurate predictions. Poor-quality or incomplete data can lead to inaccurate results and recommendations (Chaudhary, 2025).
- **Technical Expertise:** The adoption of AI technologies requires technical knowledge, which may be a barrier for some farmers. Training and support are

needed to ensure successful implementation (Folorunso et al., 2023).

- **Cost:** While the long-term benefits of AI are significant, the initial investment in AI technologies can be high, especially for smallholder farmers. However, as AI systems become more widely adopted, costs are expected to decrease (Rosca, 2025).

6. TECHNOLOGICAL LIMITATIONS

While digital and sensor-based technologies have incredibly advanced soil health monitoring, several technological limitations hinder their widespread and effective implementation. These limitations can affect the accuracy, reliability, and scalability of the systems used for monitoring soil conditions.

Sensor Accuracy and Calibration: One of the primary challenges in sensor-based monitoring is ensuring the accuracy and reliability of the sensors used to measure soil properties such as moisture, pH, and temperature. Sensors can be affected by environmental conditions, such as high salinity, extreme temperatures, or soil compaction, which can lead to inaccurate measurements. Proper calibration of sensors is crucial to obtain reliable data, but this process can be time-consuming and expensive (Folorunso, Ojo, & Busari, 2023).

Durability and Maintenance: Soil sensors, particularly those deployed in field conditions, are exposed to a range of environmental factors that can affect their longevity and performance. Factors such as soil erosion, high moisture content, extreme temperatures, and physical wear can cause sensors to degrade over time. Regular maintenance, calibration, and replacement are necessary to ensure that sensors continue to deliver accurate data. In remote agricultural areas, access to technical support and maintenance services can be a significant challenge (Schweng et al., 2026).

Data Quality and Integration: The effectiveness of digital and sensor-based tools depends mainly on the quality of the data they collect. Poor-quality data, whether due to faulty sensors, environmental interference, or human error, can lead to incorrect interpretations and recommendations. Additionally, integrating data from multiple sensors, drones, satellites, and other sources can be challenging. Differences in data formats, sensor compatibility, and data

processing methods can hinder seamless integration, making it difficult to create comprehensive soil health profiles (Chaudhary, 2025).

6.1 Economic Barriers

Despite the clear benefits of digital and sensor-based technologies for soil health monitoring, economic barriers remain a significant obstacle for widespread adoption, particularly among smallholder farmers and those in developing regions.

High Initial Costs: The upfront costs of acquiring soil sensors, remote sensing devices (e.g., drones), and digital platforms can be prohibitively expensive for smallholder farmers, particularly in low-income areas. The costs not only cover the hardware but also the software, data storage, and ongoing system maintenance (Vhatkar, 2025). Additionally, specialised training may be required for farmers to effectively use and interpret the data provided by these technologies, further increasing the cost of adoption.

Limited Access to Financing: Many farmers, particularly those in developing countries, may have limited access to credit or financing options to invest in these technologies. Government subsidies, financial support from NGOs, or loans may be required to help small-scale farmers adopt advanced soil health monitoring systems. However, such financial aid may be scarce or unavailable in certain regions, which restricts the ability of farmers to adopt and benefit from these technologies (Folorunso et al., 2023).

Cost-Effectiveness of Scale: While digital and sensor-based systems offer clear advantages in large-scale farming operations, they may not always be cost-effective for smaller farms. For smallholder farmers, the benefits of precise soil management may not outweigh the initial and ongoing costs, especially if the farm size is too small to generate a return on investment (Pandey et al., 2025). To overcome this, affordable, scalable solutions are needed that cater to the financial realities of small-scale farmers.

6.2 Data Management and Analysis

The rapid growth in data collected from sensors, drones, and other digital tools presents significant challenges in terms of data management, analysis, and storage.

Big Data Handling: Modern soil health monitoring systems generate large volumes of data, often referred to as "big data." Managing this data, particularly in agricultural operations that use multiple sensors and remote sensing technologies, can be challenging. Farmers and agronomists must have access to robust data storage systems, reliable internet connections, and software capable of handling and processing this large amount of information (Schweng et al., 2026). The capacity to process and interpret big data is a growing challenge that requires technological advancements in data storage and management.

Data Interpretation and Decision-Making: Even with high-quality data, deriving actionable insights from it remains a complex challenge. Farmers need to understand the raw data and integrate it with other factors, such as crop type, local environmental conditions, and weather patterns. This requires specialised knowledge and training in data analysis and decision-making, which may not always be accessible to farmers in rural areas (Vhatkar, 2025).

Data Privacy and Security: As soil health data is increasingly stored on cloud-based platforms, concerns about data privacy and security are becoming more prominent. Farmers may be hesitant to share their farm data due to concerns about privacy breaches or misuse of sensitive information. Ensuring that data storage and sharing protocols are secure and transparent is essential to building trust in digital soil health monitoring tools (Chaudhary, 2025).

6.3 Adoption Issues

Despite the clear benefits of digital and sensor-based tools, several adoption issues prevent widespread use, especially among smallholder farmers and in developing countries.

Awareness and Training: Many farmers are still unaware of the potential benefits that digital and sensor-based technologies offer for soil health monitoring. Limited awareness of these tools, coupled with restricted access to training, hinders farmers' adoption of these technologies. For widespread adoption to occur, educational programs and workshops are needed to raise awareness and train farmers on how to use digital tools and interpret sensor data effectively (Folorunso et al., 2023).

Cultural Resistance: In some regions, farmers may resist adopting new technologies due to

cultural factors or a reliance on traditional farming methods. In many cases, there is a strong preference for using established practices, and farmers may be hesitant to trust technology, especially when the benefits are not immediately apparent or quantifiable (Schweng et al., 2026).

Lack of Local Support: For successful adoption, farmers need access to local technical support and maintenance services for their digital and sensor-based tools. However, in rural or remote regions, the lack of local expertise and service infrastructure can make it difficult for farmers to maintain and troubleshoot their systems. This lack of support can discourage adoption and lead to poor performance or system failures (Vhatkar, 2025, Kim, et al., 2009).

6.4 Overcoming the Challenges

To overcome these challenges and limitations, several strategies can be employed:

Affordable and Scalable Solutions: Developing cost-effective, scalable soil health monitoring systems will make these technologies more accessible to smallholder farmers. Collaborative efforts between governments, NGOs, and the private sector can help subsidise the cost of technology and provide training programs to make the tools more accessible.

Improved Data Management Tools: Advancements in data storage, cloud computing, and big data analytics enable farmers to manage and interpret soil health data more effectively. Simplifying data analysis and presenting the information in user-friendly formats can make these systems more accessible to farmers without advanced technical expertise.

Government Support and Policy: Governments can play a crucial role by offering incentives, subsidies, and financial support for farmers to adopt digital and sensor-based soil health monitoring technologies. Policies that promote research and development in affordable and accessible technologies will also facilitate wider adoption (Pandey et al., 2025).

7. FUTURE DIRECTIONS IN SOIL HEALTH MONITORING

7.1 Innovations on the Horizon

The future of soil health monitoring is bright, with numerous innovations on the horizon that

promise to enhance further the accuracy, efficiency, and scalability of soil management practices. As technological advancements continue to unfold, new tools and techniques will emerge, revolutionising how soil health is monitored and managed.

- **Next-Generation Sensors:** One of the most exciting developments in soil health monitoring is the emergence of next-generation sensors. These sensors will be smaller, more cost-effective, and capable of measuring a wider range of soil parameters in real-time. For instance, sensors that can simultaneously measure soil moisture, temperature, pH, electrical conductivity, and nutrient levels are already being developed. These multi-functional sensors will allow for more comprehensive soil health assessments, making it easier for farmers to monitor and manage soil conditions on a micro-scale.
- **Nano-Sensors and Smart Soils:** Research is underway to develop nano-sensors that can detect microscopic changes in soil properties, such as microbial activity and trace nutrient levels. These sensors can be embedded within the soil itself, creating "smart soils" that continuously communicate data to farmers in real-time. This could lead to more precise soil management, as farmers would be able to respond to even the most minor changes in soil health before they become problematic.
- **Artificial Intelligence and Automation:** AI and machine learning will play an even more prominent role in the future of soil health monitoring. These technologies will not only improve predictive models for soil conditions but will also automate decision-making processes. For example, AI-driven systems could automatically adjust irrigation, fertilisation, and pest control measures based on real-time soil data, reducing human intervention and ensuring optimal soil health management.

7.2 Global Adoption and Scaling

While soil health monitoring technologies have the potential to revolutionise agriculture, their widespread adoption and global scaling remain significant challenges. To truly harness the benefits of these innovations, efforts must be made to ensure that these technologies reach farmers worldwide, particularly those in developing regions.

- **Affordability and Accessibility:** One of the key challenges to global adoption is the high cost of soil health monitoring systems, including sensors, drones, and farm management software. To promote adoption, manufacturers will need to develop more affordable and accessible solutions for smallholder farmers. Collaborative efforts from governments, NGOs, and private companies could help subsidise the costs and make these technologies more widely available to farmers in developing countries.
- **Connectivity and Data Infrastructure:** In many rural areas, especially in developing regions, there is a lack of reliable internet access and data infrastructure, which limits the effectiveness of cloud-based soil health monitoring systems. For these systems to work efficiently, a robust communication network is required to transmit data in real-time. Governments and organisations can help bridge this gap by investing in rural broadband infrastructure and supporting initiatives that improve data connectivity in agricultural regions.
- **Education and Training:** To ensure successful adoption, farmers need proper training on how to use digital and sensor-based tools. Educational programs, workshops, and online courses can help farmers understand the value of soil health monitoring technologies and teach them how to interpret the data they receive. Partnerships between agricultural tech companies, universities, and government agencies can play a pivotal role in delivering this training to farmers globally.

7.3 Policy and Regulatory Considerations

Government policies and regulations will be key to the successful scaling and adoption of soil health monitoring technologies. Policymakers can play an instrumental role by creating an environment that encourages innovation, supports research and development, and provides financial incentives for farmers to adopt these technologies.

- **Incentives and Subsidies:** Governments can offer financial incentives, such as subsidies or tax breaks, to farmers who invest in soil health monitoring

technologies. This could help offset the initial high costs associated with purchasing sensors, drones, and software. In addition, public funding could support the development of low-cost, high-performance technologies that cater to smallholder farmers in developing regions.

- **Regulation of Data Privacy and Security:** As soil health monitoring systems become more data-driven, ensuring the privacy and security of farmers' data will be essential. Governments and regulatory bodies need to establish clear policies on data ownership, privacy, and security to build trust among farmers. Regulations should ensure that farmers' personal and business data are protected from unauthorised access and misuse.
- **Standards for Data Sharing and Interoperability:** With the growing use of digital tools, sensors, and remote sensing technologies, there is a need for common standards for data sharing and system interoperability. Policymakers can encourage the development of open standards that allow different soil health monitoring systems to communicate with one another. This will help create a more integrated and seamless ecosystem for soil health management.

7.4 Future Collaborations and Research

Collaboration between the private sector, governments, research institutions, and farmers will be critical for advancing soil health monitoring technologies. Ongoing research and development will drive innovations in sensor technologies, AI-driven analytics, and data management systems.

- **Private Sector Investment:** Private companies that develop soil health monitoring tools will need to continue investing in R&D to create more affordable, scalable, and efficient systems. These companies can also collaborate with agricultural extension services to ensure that their technologies are appropriately integrated into farmers' workflows.
- **Public-Private Partnerships:** Public-private partnerships can play a vital role in scaling soil health monitoring technologies. Governments and research organisations can collaborate with tech

companies to develop and distribute soil health monitoring systems that meet the needs of farmers. These partnerships can also help secure funding for large-scale pilot projects that demonstrate the effectiveness of these technologies in real-world settings.

- **Community-Driven Research:** Engaging farmers in the development of new soil health monitoring tools will ensure that these technologies meet the needs of the end users. Community-driven research initiatives that involve farmers in testing and providing feedback on new technologies will help create solutions that are practical, affordable, and effective (Senapaty et al., 2023).

8. CONCLUSION

Soil health is crucial for the sustainability and productivity of agriculture. As global populations grow and natural resource pressures rise, adopting technologies that effectively monitor and manage soil health is essential. Advancements in digital tools, sensors, and AI have transformed soil health monitoring by providing more accurate, real-time data, allowing farmers to improve soil management practices and optimise crop yields.

This review has explored the innovations and challenges in soil health monitoring, highlighting how sensor-based technologies and AI-driven models enhance precision, prediction, and proactive management of soil conditions. While these technologies offer significant potential, challenges such as sensor accuracy, data management, economic barriers, and the need for training remain, especially in developing regions.

The future of soil health monitoring is promising, thanks to the development of next-generation sensors, nano-sensors, and AI systems that provide even more detailed insights. Global adoption of these technologies requires policies that support affordability, scalability, and infrastructure, ensuring widespread access for farmers.

Despite the challenges, the potential benefits of advanced soil health monitoring tools are vast. By fostering innovation, collaboration, and addressing adoption barriers, we can ensure a future where soil health is optimised for both productivity and sustainability, securing food

systems and environmental health for generations to come.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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