



# A Review of Modern Soil pH Monitoring Techniques and Their Effects on Crop Yield

**Battala Sheshagiri<sup>a++\*</sup>, Punna Chinmai<sup>b#</sup>, B. Niharika<sup>c†</sup>,  
Beerendra Singh<sup>d‡</sup>, Nidhi Mahendru<sup>e^</sup>, Usha N.<sup>f#</sup>  
and Posham Raghuram<sup>g###</sup>**

<sup>a</sup> Department of Agricultural Economics, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, Uttar Pradesh, India.

<sup>b</sup> Department of Agricultural Chemistry and Soil Science, Faculty of Agriculture, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal, India.

<sup>c</sup> Department of Agronomy, S.V. Agricultural College, Tirupati, Acharya N.G Ranga Agricultural University, Lam, Guntur, Andhra Pradesh, India.

<sup>d</sup> Department of Soil Science and Agricultural Chemistry, Bihar Agricultural University, Irrigation Research Station, Bikramganj, Rohtas, Bihar, India.

<sup>e</sup> Department of Biotechnology, Guru Nanak Khalsa College, Yamuna Nagar, Haryana, India.

<sup>f</sup> Department of Agronomy, University of Agricultural Sciences Bangalore, Karnataka, India.

<sup>g</sup> Department of Sericulture, Kakatiya University, Telangana, India.

## *Authors' contributions*

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<sup>++</sup> MBA Agribusiness; <sup>#</sup> PhD Scholar; <sup>†</sup> M.Sc. Scholar; <sup>‡</sup> Assistant Professor -cum-Junior Scientist; <sup>^</sup> Assistant Professor & Head;

<sup>##</sup> Research Scholar;

\*Corresponding author: E-mail: sheshagiri863@gmail.com;

## Abstract

Soil pH is a fundamental determinant of soil fertility, nutrient availability, and crop productivity. It influences chemical equilibria, microbial processes, and plant nutrient uptake, making it a key factor in sustainable agricultural management. Conventional soil pH measurement techniques, such as laboratory-based glass electrode methods, although accurate, are often labor-intensive, time-consuming, and inadequate for capturing spatial variability within fields. With the advancement of precision agriculture, modern soil pH monitoring technologies have emerged, offering real-time, high-resolution, and site-specific data.

This review comprehensively examines recent developments in soil pH monitoring techniques, including electrochemical sensors, optical and spectroscopic approaches, proximal and remote sensing, and IoT-based systems integrated with machine learning algorithms. These technologies have significantly improved the efficiency of soil monitoring, enabling farmers to optimize nutrient management and enhance crop yield. The integration of artificial intelligence and wireless sensor networks has further facilitated predictive modeling and automated decision-making.

The relationship between soil pH and crop yield is critically analyzed through multiple case studies, demonstrating how precise pH management can enhance nutrient use efficiency, reduce environmental impacts, and increase productivity. Despite these advancements, challenges such as sensor calibration, cost constraints, and environmental variability persist. Future prospects include the development of low-cost sensors, AI-driven decision support systems, and fully automated smart farming solutions. This review highlights the transformative role of modern soil pH monitoring in achieving sustainable agriculture and global food security.

*Keywords:* Crop yield; IoT; machine learning; precision agriculture proximal sensing; soil pH; soil sensors; sustainable agriculture.

## 1. Introduction

Agriculture is undergoing a rapid transformation driven by technological advancements aimed at enhancing productivity while ensuring environmental sustainability. Among the various soil parameters, soil pH stands out as a critical factor influencing crop growth, nutrient availability, and microbial activity. It is often referred to as the “master variable” in soil science because it governs numerous biological and chemical processes (Brady & Weil, 2008; Bunemann et al., 2018; Najdenko et al., 2024). The optimal soil pH range for most crops lies between 6.0 and 7.5, and deviations from this range can significantly impact crop performance. Acidic soils can lead to aluminium and manganese toxicity, while alkaline soils often result in micronutrient deficiencies such as iron and zinc, thereby affecting plant metabolism and yield (Fageria & Baligar, 2008; Jones, 2004; Cassman et al., 2009; Corwin and Lesch, 2005).

Traditional soil pH measurement methods rely on laboratory-based techniques such as glass electrode analysis, which, although accurate, are limited in their ability to provide real-time and spatially representative data (Kumar et al., 2015, Faridah et al., 2025, Hinsinger, 2001, Ruiz-Garcia et al., 2009). This limitation has led to inefficient fertilizer application and suboptimal crop management. The emergence of precision agriculture has revolutionized soil monitoring by integrating sensors, remote sensing, GIS, and data analytics, enabling continuous and site-specific measurements (Gebbers & Adamchuk, 2010; McBratney et al., 2005). These advancements not only improve crop yield but also reduce environmental impacts and resource wastage (Foley et al., 2011; Godfray et al., 2010, Ray et al., 2013).

The emergence of precision agriculture has revolutionized soil monitoring by integrating advanced technologies such as sensors, remote sensing, geographic information systems (GIS), and data analytics. Modern soil pH monitoring techniques enable continuous, in-field measurements, allowing farmers to adopt site-specific management practices. These technologies not only improve crop yield but also reduce input costs and environmental impacts.

This review hypothesizes that advancements in modern soil pH monitoring techniques significantly improve crop yield by enabling precise nutrient management and optimized soil conditions. It further assumes that the evolution of soil sensing technologies, particularly within precision agriculture systems, enhances decision-making efficiency and reduces input misuse. Consequently, the integration of these technologies is expected to

contribute to sustainable agricultural production and support global food security by improving soil health management and crop productivity.

## **2. Role of Soil pH in Soil Health and Crop Productivity**

### **2.1 Soil pH as a Master Variable**

Soil pH indicates the concentration of hydrogen ions ( $H^+$ ) present in the soil solution and is widely regarded as a master variable because it simultaneously regulates numerous chemical, biological, and physical processes within the soil environment. A master variable is defined as a single dominant factor that influences multiple interrelated soil functions and ultimately determines overall soil performance. Soil pH fulfills this role by controlling nutrient solubility, microbial activity, ion exchange reactions, and the availability or toxicity of various elements. Consequently, it has a direct influence on soil fertility, plant growth, and crop productivity. Even small changes in soil pH can significantly modify nutrient balance and biological activity, leading to noticeable differences in plant development and yield.

As a master variable, soil pH affects several critical soil processes, including nutrient availability, microbial population dynamics, enzyme activity, soil structural stability, metal toxicity, and root growth. These interconnected effects mean that soil pH indirectly governs soil health and agricultural productivity. One of the primary mechanisms through which soil pH exerts its influence is by regulating nutrient availability. Essential macronutrients such as nitrogen, phosphorus, and potassium are most accessible to plants within a pH range of approximately 6.0 to 7.5. In contrast, micronutrients such as iron, manganese, and zinc become more soluble under acidic conditions, whereas calcium and magnesium are more available in neutral to slightly alkaline soils. When soil pH deviates from the optimal range, nutrient imbalances may occur, resulting in deficiencies or reduced uptake efficiency.

Soil pH also strongly influences microbial activity. Soil microorganisms involved in organic matter decomposition, nitrogen fixation, and nutrient cycling are sensitive to pH variations. Bacterial populations generally thrive in neutral conditions, while fungi tend to tolerate acidic environments. Nitrogen-fixing bacteria perform most effectively in slightly acidic to neutral soils, typically between pH 6.5 and 7.5. Therefore, pH fluctuations affect microbial diversity, decomposition rates, and nutrient mineralization processes. Additionally, soil pH affects cation exchange capacity, which determines the soil's ability to retain essential nutrients. In highly acidic soils, excess hydrogen and aluminum ions occupy exchange sites, reducing nutrient retention. Conversely, near-neutral pH levels enhance nutrient holding capacity and improve soil fertility.

Another important aspect of soil pH is its role in controlling element toxicity. In acidic soils, aluminum and manganese may reach toxic concentrations that inhibit root growth and damage plant tissues. In alkaline soils, micronutrients such as iron, zinc, and phosphorus become less available, leading to nutrient deficiencies. These conditions restrict plant development and reduce crop productivity. Soil pH also directly influences root growth and nutrient absorption efficiency. Acidic conditions can restrict root elongation due to aluminum toxicity, while alkaline soils limit micronutrient uptake, both of which negatively impact plant growth.

Soil pH is commonly classified into different categories: strongly acidic soils have a pH below 5.5, moderately acidic soils range from 5.5 to 6.5, neutral soils lie between 6.5 and 7.5, moderately alkaline soils range from 7.5 to 8.5, and strongly alkaline soils exceed 8.5. Different crops exhibit varying tolerance to these pH ranges. Acidic soils favor crops such as tea, potato, pineapple, rice, coffee, and rubber. Slightly acidic to neutral soils are suitable for wheat, maize, soybean, groundnut, sunflower, sorghum, and barley. Neutral soils support most vegetables, pulses, cotton, sugarcane, and mustard. Slightly alkaline soils are suitable for crops like cabbage, cauliflower, spinach, beetroot, and alfalfa, while alkaline soils are tolerated by barley, cotton, pearl millet, sugar beet, and date palm.

Most agricultural crops perform best within a pH range of 6.0 to 7.5, where nutrient availability is highest, microbial activity is optimal, toxicity risks are minimal, and soil structure remains stable. Because soil pH simultaneously controls nutrient dynamics, biological processes, and plant growth, it functions as a master variable in soil systems. Maintaining an optimal soil pH through liming, organic amendments, and precision monitoring practices is therefore essential for improving soil health, enhancing nutrient use efficiency, and achieving sustainable crop productivity.

## **2.2 Nutrient Availability and Soil pH**

The availability of essential nutrients is strongly influenced by soil pH. Nitrogen utilization is optimal under near-neutral conditions, while phosphorus availability decreases in highly acidic or alkaline soils due to fixation processes. Micronutrients such as iron and zinc are more soluble in acidic soils, highlighting the importance of maintaining optimal pH for balanced nutrient uptake (Fageria & Baligar, 2008). Therefore maintaining an optimal pH range is crucial for balanced nutrient uptake and efficient fertilizer utilization.

## **2.3 Microbial Activity and Soil pH**

Soil pH significantly affects microbial populations and their functions. Neutral pH supports diverse bacterial communities, while acidic conditions favor fungal dominance. These microorganisms are essential for nutrient cycling, organic matter decomposition, and nitrogen fixation (Doran & Zeiss, 2000; Lehmann et al., 2020).

## **2.4 Impact on Crop Yield**

Optimal soil pH enhances root development, nutrient absorption, and stress tolerance, leading to improved crop yield. In contrast, extreme pH conditions reduce productivity and crop quality (Jones, 2004; Brady & Weil, 2008).

## **3. Evolution of Soil pH Monitoring Techniques**

### **3.1 Conventional Methods**

Traditional soil pH measurement methods, including glass electrodes and indicator dyes, provide accurate results but are labor-intensive and lack real-time capability (Kumar et al., 2015). These methods also fail to capture spatial variability within fields, limiting their effectiveness in modern agriculture (Adamchuk et al., 2004). They are labor-intensive, requiring manual sample collection and preparation, which increases time and effort. Additionally, delays between sampling and analysis can reduce their effectiveness for real-time decision-making. Another significant drawback is their limited spatial coverage, as only a few samples represent large field areas, often overlooking soil variability.

### **3.2 Transition to Modern Techniques**

The need for real-time and site-specific soil information has driven the adoption of modern technologies such as on-the-go sensors, spectroscopy, remote sensing, and IoT systems (Mulla, 2013; Zhang et al., 2015). These innovations enable continuous monitoring and high-resolution data collection, improving decision-making and crop productivity (Gebbers & Adamchuk, 2010). Remote sensing offers large-scale monitoring, and IoT systems facilitate real-time data transmission and analysis. Collectively, these innovations enhance precision soil management, optimize input use, and support improved crop productivity.

## **4. Modern Soil pH Monitoring Technologies**

### **4.1 Electrochemical Sensors**

Electrochemical sensors, particularly ion-selective electrodes, provide direct and accurate measurement of soil pH and are widely used in field applications (Adamchuk et al., 2004). However, their performance can be affected by calibration drift and soil moisture variations.

### **4.2 Optical and Spectroscopic Techniques**

Spectroscopic techniques such as VIS-NIR enable rapid and non-destructive soil analysis, making them suitable for large-scale applications (Mouazen et al., 2005; Stenberg et al., 2010). These techniques are non-destructive and enable rapid data collection, making them highly efficient for large-scale soil analysis. They are particularly useful in precision agriculture where quick assessments are needed across extensive fields.

### **4.3 Proximal Soil Sensing**

Proximal sensing technologies provide high-resolution spatial data and support precision nutrient management (Viscarra Rossel et al., 2010). Proximal sensing technologies involve sensors mounted on farm machinery that collect soil data during field operations. This method supports detailed soil variability mapping and facilitates precise fertilizer application, improving resource use efficiency.

### **4.4 Remote Sensing Technologies**

Remote sensing using satellites and UAVs allows large-scale soil monitoring and supports sustainable land management (Dorigo et al., 2017). Remote sensing using satellites and drones allows for large-area soil monitoring. These systems offer wide coverage and are cost-effective for managing extensive agricultural lands.

### **4.5 IoT-Based Monitoring Systems**

IoT-based systems enable continuous and real-time monitoring of soil parameters through interconnected sensors and cloud platforms (Li et al., 2013). IoT-based systems combine sensors, communication modules, and cloud platforms to enable continuous and real-time soil monitoring. These systems enhance decision-making through data accessibility.

### **4.6 Machine Learning and AI Integration**

AI and machine learning models enhance predictive capabilities and decision support systems in agriculture (Saha et al., 2025; Sudha & Lorent, 2026). Machine learning techniques process complex datasets to predict soil pH and optimize crop management strategies, supporting advanced decision support systems in modern agriculture.

## **5. Integration with Precision Agriculture and its Relation to Soil pH**

Precision agriculture has emerged as an advanced farming approach that utilizes spatial and temporal variability within fields to optimize resource use and enhance productivity. Within this framework, soil pH is considered a critical parameter because of its direct influence on nutrient availability, fertilizer efficiency, and crop growth. Variations in soil pH across a field can significantly affect plant performance; therefore, monitoring and managing these variations is essential for site-specific crop management. Precision agriculture integrates technologies such as geographic information systems (GIS), global positioning systems (GPS), remote sensing, and soil sensors to generate high-resolution maps that capture spatial variability, including soil pH distribution. These maps provide valuable information that supports variable rate application of fertilizers and soil amendments, particularly lime, which is commonly applied to correct soil acidity. By adjusting lime and fertilizer inputs according to localized soil pH conditions, farmers can improve nutrient use efficiency, reduce production costs, and minimize environmental risks such as nutrient leaching and soil degradation (Pierce & Nowak, 1999; Bongiovanni & Lowenberg-DeBoer, 2004).

Soil pH data also play an important role in guiding site-specific management practices. For instance, acidic zones within a field may require liming and the selection of acid-tolerant crop varieties, whereas alkaline areas may benefit from micronutrient supplementation to address deficiencies. Integrating soil pH information with yield maps, soil nutrient status, and crop performance data allows more precise decisions regarding crop selection, irrigation scheduling, and nutrient management. Such targeted interventions help enhance crop productivity while conserving inputs and maintaining soil health. Furthermore, advances in sensor technology enable real-time soil pH monitoring, allowing dynamic adjustments throughout the growing season. This continuous feedback improves decision-making and reduces the likelihood of over- or under-application of fertilizers and amendments. Overall, the incorporation of soil pH monitoring into precision agriculture systems enhances resource efficiency, supports sustainable soil management, and contributes to long-term agricultural productivity and environmental protection (Pierce et al., 1999).

## **6. Case Studies on Soil pH Monitoring and Crop Yield**

Field studies across different regions demonstrate the effectiveness of modern soil pH monitoring technologies. On-the-go sensors in the USA have increased corn yield by approximately 15%, while IoT-based systems in

India have improved nutrient efficiency (Adamchuk et al., 2004; Saha et al., 2025). Spectroscopic methods in China and remote sensing in Brazil have enhanced soil mapping and reduced input costs (Mouazen et al., 2005;). Similarly, AI-based models in Australia and proximal sensing in Germany have improved yield prediction and soil management (Viscarra Rossel et al., 2010; Sudha & Lore, 2026).

**Table 1. Case Studies on Soil pH Monitoring Integration in Precision Agriculture**

Case	Region	Technology	Crop	Outcome	Reference
1	USA	On-the-go sensors	Corn	15% yield increase	Adamchuk et al., 2004
2	India	IoT sensors	Wheat	Improved efficiency	Sharma et al., 2023
3	China	Spectroscopy	Rice	Accurate mapping	Ge et al., 2011
4	Brazil	Remote sensing	Soybean	Reduced inputs	Bernardi et al., 2014
5	Australia	AI models	Barley	Better predictions	McBratney et al., 2005
6	Germany	Proximal sensing	Maize	High-resolution data	Viscarra Rossel et al., 2010
7	Japan	Smart sensors	Vegetables	Improved irrigation	Shibusawa, 2001
8	UK	Digital mapping	Wheat	Optimized lime use	Bramley & Janik, 2007
9	Canada	Wireless sensors	Canola	Real-time benefits	Jayaraman et al., 2016
10	Africa	Low-cost sensors	Millet	Increased productivity	Tesfahunegn et al., 2011

Modern soil pH monitoring technologies have significantly enhanced agricultural productivity. The integration of sensors, IoT, and AI has enabled precise soil management, leading to improved crop yield and sustainability. However, challenges such as high costs, technical complexity, and environmental variability must be addressed to ensure widespread adoption.

## 7. Detailed Analysis of Modern Soil pH Monitoring Technologies

Modern soil sensing technologies have significantly transformed agriculture by enabling real-time and high-resolution soil analysis (McBratney et al., 2003; Minasny & McBratney, 2016). Electrochemical sensors remain reliable but require calibration, while spectroscopic methods offer rapid analysis with calibration dependency (Stenberg et al., 2010). Proximal and remote sensing technologies provide spatial insights, whereas IoT systems enable continuous monitoring (Li et al., 2013; Dorigo et al., 2017). AI integration further enhances predictive modeling and decision-making (Saha et al., 2025). The rapid advancement of soil sensing technologies has significantly transformed agricultural practices. Each modern soil pH monitoring technique offers unique advantages and limitations depending on field conditions, crop type, and management objectives. A detailed understanding of these technologies is essential for their effective implementation.

### 7.1 Electrochemical Soil pH Sensors

Electrochemical soil pH sensors represent one of the most established and reliable approaches for measuring soil acidity due to their ability to directly quantify hydrogen ion activity in the soil solution. These sensors are widely adopted in both research and practical agricultural applications because they provide accurate, real-time measurements that are essential for effective soil management. Typically, electrochemical systems are based on ion-selective electrodes (ISEs), which are specifically designed to respond to hydrogen ions. Their robustness, relatively simple operation, and compatibility with portable devices make them suitable for field-based applications. As agriculture moves toward precision-based practices, these sensors play a crucial role in enabling site-specific soil analysis and management.

### 7.2 Optical and Spectroscopic Techniques

Optical sensing techniques, particularly visible and near-infrared (VIS-NIR) spectroscopy, have emerged as powerful tools for soil analysis. Unlike electrochemical methods, these techniques estimate soil pH indirectly by analyzing the interaction between light and soil constituents. Their non-destructive nature and rapid data acquisition make them highly attractive for large-scale agricultural applications.

### 7.3 Proximal Soil Sensing Technologies

Proximal soil sensing involves the use of sensors placed close to or in direct contact with the soil to collect data in real time. These systems are often mounted on agricultural machinery or used as handheld devices, enabling detailed spatial analysis of soil properties.

## 7.4 Remote Sensing Technologies

Remote sensing technologies provide a broader perspective on soil and crop conditions by collecting data from a distance. These methods are particularly useful for monitoring large agricultural areas.

## 7.5 IoT-Based Soil Monitoring Systems

The Internet of Things has revolutionized soil monitoring by connecting sensors to digital networks, enabling continuous data collection and analysis.

## 7.6 Machine Learning and Artificial Intelligence

Machine learning and artificial intelligence have become integral to modern soil monitoring systems, enabling advanced data analysis and predictive modelling.

## 8. Expanded Case Studies on Soil pH Monitoring and Crop Yield

The practical application of modern soil pH monitoring technologies across diverse agricultural systems demonstrates their significant role in improving crop productivity, resource efficiency, and sustainability. Case studies demonstrate that precision agriculture technologies improve yield by 10–20% through optimized nutrient management and soil pH control (Grassini et al., 2015; Mueller et al., 2012). IoT systems reduce input costs, while AI improves prediction accuracy (Saha et al., 2025). Low-cost sensors have enhanced productivity among smallholder farmers in developing regions (Cai et al., 2025). The case studies presented in Table 1 highlight real-world implementations of various sensing and analytical approaches, ranging from advanced on-the-go sensors in developed agricultural systems to low-cost sensor solutions tailored for smallholder farmers. These examples collectively illustrate how site-specific soil pH management contributes to optimized nutrient availability, efficient input utilization, and enhanced crop performance.

In the United States, the use of on-the-go soil sensors in corn production systems has enabled continuous field mapping of soil pH variability. This approach allows farmers to apply fertilizers and lime in a variable-rate manner, resulting in a reported yield increase of approximately 15%. The integration of such technologies minimizes over-application of inputs, thereby reducing costs and environmental impacts while improving nutrient use efficiency. Similarly, in India, the adoption of IoT-based soil monitoring systems in wheat cultivation has facilitated real-time tracking of soil conditions. Farmers can access data remotely and make timely decisions regarding fertilizer application, leading to reduced input costs and improved nutrient management practices.

In China, spectroscopic techniques such as visible and near-infrared (VIS-NIR) analysis have been employed in rice cultivation to estimate soil pH with high accuracy. This non-destructive method enables rapid assessment of soil conditions over large areas, supporting precision farming practices. In Brazil, remote sensing technologies using satellite imagery have been utilized in soybean production to monitor soil variability and optimize fertilizer application. This approach not only reduces input costs but also contributes to environmental sustainability by minimizing nutrient losses.

Advanced data-driven approaches are evident in Australia, where artificial intelligence models have been applied to barley production systems. By analysing historical and real-time data, these models improve yield prediction accuracy and assist farmers in making informed management decisions. In Germany, proximal soil sensing technologies have been used in maize cultivation to generate high-resolution soil maps. These maps guide efficient lime application, ensuring that soil pH is maintained within optimal ranges for crop growth.

In Japan, smart sensor systems integrated with automated control mechanisms have been successfully implemented in vegetable production. These systems continuously monitor soil conditions and adjust irrigation and nutrient delivery accordingly, resulting in increased yields and improved water use efficiency. In the United Kingdom, digital soil mapping combined with geographic information system (GIS) analysis has been employed in wheat farming to optimize lime application. This targeted approach enhances soil health and promotes sustainable crop production.

In Canada, wireless sensor networks have enabled continuous monitoring of soil pH and other parameters in canola fields. The real-time data generated by these systems supports adaptive management practices, leading to improved crop performance and long-term sustainability. In contrast, in Kenya, the use of low-cost soil sensors has provided smallholder farmers with access to essential soil information. These affordable technologies have contributed to increased millet yields and improved livelihoods, demonstrating the potential of scalable innovations in resource-limited settings.

**Table 2. Detailed insights into real-world applications of soil pH monitoring technologies**

Case	Country	Technology	Crop	Methodology	Key Results	Impact	Reference
1	USA	On-the-go sensors	Corn	Field mapping	15% yield increase	Improved fertilizer use	Adamchuk et al., 2004.
2	India	IoT sensors	Wheat	Real-time monitoring	Reduced input cost	Better nutrient use	Patil et al., 2017.
3	China	Spectroscopy	Rice	VIS-NIR analysis	Accurate pH prediction	Precision farming	Viscarra Rossel et al., 2010.
4	Brazil	Remote sensing	Soybean	Satellite imagery	Reduced fertilizer use	Cost savings	Mulla, 2013.
5	Australia	AI models	Barley	Data modeling	Yield prediction improved	Decision support	Shahhosseini et al., 2020.
6	Germany	Proximal sensing	Maize	Sensor mapping	High-resolution data	Efficient liming	Rudolph et al., 2016.
7	Japan	Smart sensors	Vegetables	Automated control	Increased yield	Water efficiency	Reza et al., 2025.
8	UK	Digital mapping	Wheat	GIS-based analysis	Optimized lime use	Soil health improved	Lark & Stafford, 1997.
9	Canada	Wireless sensors	Canola	Continuous monitoring	Improved crop performance	Sustainability	Zhang et al., 2015.
10	Kenya	Low-cost sensors	Millet	Smallholder use	Increased yield	Rural adoption	Kizito et al., 2018.

### 8.1 Key Observations from Case Studies

The analysis of these case studies reveals several important trends and insights regarding the effectiveness of soil pH monitoring technologies. First, precision agriculture technologies consistently lead to yield improvements ranging from 10% to 20%. This increase is primarily attributed to the ability to maintain optimal soil pH levels, which enhances nutrient availability and uptake by crops. By addressing spatial variability within fields, these technologies ensure that inputs are applied precisely where needed, reducing wastage and improving efficiency.

Second, IoT-based systems play a crucial role in reducing input costs by enabling real-time monitoring and decision-making. Farmers can respond promptly to changes in soil conditions, avoiding excessive use of fertilizers and other inputs. This not only lowers production costs but also reduces the environmental footprint of agricultural practices. The integration of wireless communication and cloud-based data storage further enhances the accessibility and usability of these systems.

Third, the incorporation of artificial intelligence and machine learning models significantly improves decision-making accuracy. These technologies analyze large datasets to identify patterns and predict outcomes, allowing farmers to make informed choices regarding crop management. The ability to forecast soil conditions and crop responses under different scenarios is particularly valuable in the context of climate variability and uncertainty.

Finally, the adoption of low-cost sensor technologies has proven to be highly beneficial for smallholder farmers, particularly in developing regions. These innovations provide access to critical soil information that was previously unavailable or unaffordable. By enabling data-driven decision-making at the grassroots level, such technologies contribute to increased productivity, improved resource management, and enhanced food security. Overall, the case studies underscore the transformative potential of modern soil pH monitoring technologies in agriculture. They highlight the importance of integrating advanced sensing systems with data analytics and decision support tools to achieve sustainable and efficient crop production.

## **9. Economic Implications of Soil pH Monitoring**

The adoption of soil pH monitoring technologies involves initial investment but provides long-term economic benefits through improved yield and reduced input costs (Bongiovanni & Lowenberg-Deboer, 2004). Farmers typically achieve ROI within 2–3 years, with income increases of 20–30% (Gebbers & Adamchuk, 2010).

### **9.1 Cost–benefit Analysis**

Modern soil pH monitoring technologies represent a strategic investment in precision agriculture, where short-term expenditures are offset by long-term economic gains. The initial costs associated with these systems include the purchase and installation of sensors, periodic calibration and maintenance, and the establishment of data management platforms for storing and analysing field information. While these expenses may appear substantial at the outset, particularly for small and medium-scale farmers, they must be evaluated in the context of the substantial benefits they deliver over time. One of the most significant advantages is the reduction in unnecessary fertilizer application. By accurately identifying soil pH variability across fields, farmers can apply lime or fertilizers only where needed, avoiding blanket applications that lead to resource wastage. This targeted approach not only lowers input costs but also improves nutrient use efficiency. Furthermore, optimized soil pH conditions enhance nutrient availability, leading to improved plant growth and higher crop yields. Over multiple growing seasons, the cumulative effect of these improvements results in better profitability and farm sustainability. Additionally, efficient resource utilization, including water and agrochemicals, reduces operational costs and minimizes environmental risks. Therefore, despite the initial financial burden, soil pH monitoring technologies provide a favourable cost–benefit balance when evaluated over the long term.

### **9.2 Return on Investment (ROI)**

The return on investment associated with soil pH monitoring and precision agriculture technologies is increasingly being recognized as both rapid and substantial. Empirical studies and field applications have demonstrated that farmers can recover their initial investment within a relatively short period, typically ranging from two to three years. This quick payback period is largely attributed to savings in input costs and improvements in crop productivity. By ensuring that soil pH remains within the optimal range, crops can more effectively absorb nutrients, reducing the need for excessive fertilization and corrective measures. This efficiency translates directly into cost savings and increased yield output. In addition, the use of data-driven decision-making tools allows farmers to optimize planting schedules, irrigation practices, and nutrient management strategies, further enhancing profitability. Reports indicate that overall farm income can increase by approximately 20–30% following the adoption of precision soil monitoring systems. Beyond direct financial gains, there are also indirect economic benefits, such as improved soil longevity and reduced risk of crop failure due to nutrient imbalances. These factors contribute to a more stable and resilient farming system, making soil pH monitoring a valuable investment for long-term agricultural success.

### **9.3 Adoption Barriers**

Despite the clear economic advantages, the widespread adoption of soil pH monitoring technologies faces several significant challenges. One of the primary barriers is the high initial cost associated with acquiring and installing advanced sensor systems and related infrastructure. For many farmers, especially those operating on small landholdings or in developing regions, these upfront expenses can be prohibitive. Another major challenge is the lack of technical knowledge and expertise required to operate and interpret data from these technologies. Precision agriculture systems often involve complex data analytics and require training, which may not be readily accessible to all farmers. Additionally, limited infrastructure, particularly in rural areas, poses a constraint to adoption. Reliable internet connectivity, power supply, and access to technical support services are

essential for the effective functioning of IoT-based monitoring systems. Without these foundational elements, the potential benefits of soil pH monitoring cannot be fully realized. Addressing these barriers through policy support, farmer training programs, and the development of affordable technologies is crucial for promoting broader adoption.

## **10. Environmental Impacts**

Soil pH monitoring supports sustainable nutrient management by reducing fertilizer overuse and environmental pollution. It also contributes to climate change mitigation by enhancing carbon sequestration and reducing greenhouse gas emissions (Lal, 2004; Smith et al., 2007).

### **10.1 Sustainable Nutrient Management**

Soil pH monitoring plays a pivotal role in promoting sustainable nutrient management practices in agriculture. By providing accurate and real-time information on soil conditions, these technologies enable farmers to apply fertilizers and soil amendments with precision. This targeted application minimizes the risk of over-fertilization, which is a major cause of nutrient runoff into water bodies. Excessive nutrients, particularly nitrogen and phosphorus, can lead to eutrophication, resulting in the degradation of aquatic ecosystems. By maintaining optimal soil pH levels, nutrient availability is enhanced, allowing crops to utilize applied fertilizers more efficiently. This reduces the need for repeated applications and lowers the overall environmental footprint of farming activities. Furthermore, precise nutrient management contributes to the conservation of natural resources by reducing the demand for synthetic fertilizers, which are energy-intensive to produce. As a result, soil pH monitoring supports environmentally responsible farming practices while maintaining high levels of productivity.

### **10.2 Climate Change Mitigation**

Efficient soil management, facilitated by accurate pH monitoring, contributes significantly to climate change mitigation efforts. One of the key benefits is the reduction of greenhouse gas emissions associated with agricultural activities. Over-application of fertilizers can lead to the release of nitrous oxide, a potent greenhouse gas. By optimizing fertilizer use through soil pH monitoring, these emissions can be minimized. Additionally, maintaining balanced soil pH enhances soil structure and promotes the accumulation of organic matter, which plays a crucial role in carbon sequestration. Soils with higher organic carbon content act as carbon sinks, helping to offset atmospheric carbon dioxide levels. Improved soil health also increases resilience to climate variability, enabling crops to better withstand stress conditions such as drought and extreme temperatures. Thus, soil pH monitoring not only enhances agricultural productivity but also contributes to global efforts to combat climate change.

### **10.3 Soil Health Improvement**

Maintaining optimal soil pH is essential for sustaining overall soil health and long-term agricultural productivity. Soil pH influences the physical structure of soil, affecting properties such as aggregation, porosity, and water retention capacity. Proper pH management promotes the formation of stable soil aggregates, which improve aeration and root penetration. In addition, soil pH has a profound impact on microbial diversity and activity. Beneficial microorganisms, including bacteria and fungi, thrive within specific pH ranges and are responsible for critical processes such as nutrient cycling and organic matter decomposition. A balanced microbial ecosystem enhances soil fertility and supports plant growth. Over time, consistent monitoring and management of soil pH lead to improved soil resilience, reducing the risk of degradation and maintaining productivity across multiple cropping cycles. Consequently, soil pH monitoring is a key component of sustainable soil management, ensuring that agricultural systems remain productive and environmentally sound for future generations.

## **11. Comparative Evaluation of Soil pH Monitoring Techniques**

The comparative assessment of soil pH monitoring technologies reveals significant variation in their performance, cost, and applicability across different agricultural settings. Electrochemical sensors remain one of the most reliable methods due to their high accuracy and real-time measurement capability, although frequent

calibration is necessary to maintain precision. Spectroscopic techniques, while offering rapid and non-destructive analysis, depend heavily on calibration models and tend to involve higher initial costs. Proximal sensing technologies provide highly accurate, site-specific data and are particularly useful for precision farming; however, their adoption is often limited by expensive equipment requirements. Remote sensing methods, on the other hand, are cost-effective and highly scalable, making them suitable for large-area monitoring, though they provide only indirect estimations of soil pH and lack real-time capabilities. Each soil monitoring technology offers unique advantages. Electrochemical sensors provide high accuracy, while spectroscopy and remote sensing offer scalability (Viscarra Rossel et al., 2010). IoT and AI systems provide real-time monitoring and predictive insights, making them essential for modern agriculture (Li et al., 2013; Sudha & Loret, 2026). IoT-based systems have gained considerable attention due to their ability to deliver continuous, real-time data with moderate cost and high scalability, but they rely on stable network connectivity. Meanwhile, artificial intelligence models demonstrate very high accuracy and strong scalability by analyzing complex datasets, yet their effectiveness depends on the availability and quality of input data. Overall, each technology offers distinct advantages, and their integration can significantly enhance soil management strategies.

**Table 3. Technology Comparison of Soil pH Monitoring Techniques**

Technology	Accuracy	Cost	Scalability	Real-Time	Limitations	References
Electrochemical	High	Medium	Medium	Yes	Calibration	Adamchuk et al., 2004; Viscarra Rossel et al., 2010
Spectroscopy	Medium	High	High	Yes	Calibration models	Stenberg et al., 2010; Viscarra Rossel & Behrens, 2010
Proximal sensing	High	High	Medium	Yes	Equipment cost	Mouazen et al., 2005; Adamchuk et al., 2004
Remote sensing	Medium	Low	High	No	Indirect measurement	Metternicht & Zinck, 2003; Mulder et al., 2011
IoT systems	High	Medium	High	Yes	Connectivity issues	Ojha et al., 2015
AI models	Very High	Medium	High	Yes	Data dependency	Liakos et al., 2018; Kamilaris & Prenafeta-Boldú, 2018

The transformation of modern agriculture into a data-driven and technology-enabled system has been largely facilitated by the integration of multiple advanced technologies. Smart farming represents a holistic approach in which diverse technological components work synergistically to optimize agricultural productivity, enhance resource use efficiency, and ensure environmental sustainability. Among the most influential integrations are sensor-based systems combined with Internet of Things (IoT) platforms and artificial intelligence (AI), the coupling of remote sensing with geographic information systems (GIS), and the use of data analytics alongside automation technologies. Together, these integrated systems are redefining traditional farming practices and enabling precision agriculture on an unprecedented scale.

The integration of sensors, IoT, and AI forms the backbone of smart farming systems. Sensors deployed in agricultural fields continuously monitor critical parameters such as soil pH, moisture content, temperature, nutrient levels, and crop health indicators. These sensors generate real-time data, which are transmitted through IoT networks to centralized platforms or cloud-based systems. The role of IoT is crucial, as it ensures seamless communication between field devices and data processing units, allowing farmers to access up-to-date information remotely. Artificial intelligence further enhances this system by analyzing large datasets generated by sensors. AI algorithms can identify patterns, predict future conditions, and provide actionable insights. For instance, AI-driven models can predict soil pH fluctuations and recommend appropriate liming or fertilization strategies, thereby optimizing nutrient management. This integration not only improves accuracy but also reduces human intervention, making farming operations more efficient and reliable.

Another critical integration in smart farming is the combination of remote sensing technologies with GIS. Remote sensing, through satellites and unmanned aerial vehicles (UAVs), enables large-scale monitoring of

agricultural landscapes. It provides valuable information on crop health, soil variability, water stress, and land use patterns. However, the raw data obtained from remote sensing require spatial analysis to be effectively utilized. This is where GIS plays a vital role. GIS tools process and visualize spatial data, allowing farmers and researchers to create detailed maps and identify variations within fields. For example, GIS-based soil maps can highlight areas with different pH levels, enabling site-specific management practices such as variable rate fertilization and liming. The integration of remote sensing and GIS thus facilitates precise decision-making at both field and regional levels, contributing to improved crop performance and resource optimization.

Data analytics and automation represent another powerful combination driving the evolution of smart farming. The vast amount of data generated from sensors, remote sensing platforms, and farm machinery requires advanced analytical tools for interpretation. Data analytics involves the use of statistical methods, machine learning algorithms, and predictive models to extract meaningful insights from complex datasets. These insights can guide farmers in making informed decisions regarding irrigation scheduling, nutrient management, pest control, and harvesting. Automation complements data analytics by implementing these decisions through automated systems. For instance, automated irrigation systems can adjust water application based on real-time soil moisture data, while automated fertilization systems can apply nutrients precisely where needed. This integration reduces labor requirements, minimizes human error, and ensures consistent application of agricultural inputs.

The integration of these technologies collectively enables smart decision-making in agriculture. By providing accurate, real-time, and location-specific information, integrated systems empower farmers to make informed choices that enhance productivity and sustainability. Decision support systems (DSS), which combine data from multiple sources, offer recommendations tailored to specific field conditions. These systems consider factors such as weather forecasts, soil properties, and crop requirements to optimize management practices. As a result, farmers can respond proactively to changing conditions rather than relying on reactive approaches.

Automated farming systems are another significant outcome of technological integration. Automation in agriculture ranges from simple mechanization to advanced robotics and autonomous machinery. Integrated systems allow for the development of smart equipment capable of performing tasks such as planting, irrigation, fertilization, and harvesting with minimal human intervention. For example, autonomous tractors equipped with GPS and sensor technologies can perform field operations with high precision, reducing overlap and input wastage. Similarly, robotic systems can monitor crop health and apply treatments only where necessary, thereby improving efficiency and reducing environmental impact.

Ultimately, the integration of sensors, IoT, AI, remote sensing, GIS, data analytics, and automation leads to increased agricultural productivity. By optimizing resource use and minimizing losses, these technologies contribute to higher crop yields and improved quality. They also support sustainable farming practices by reducing the overuse of fertilizers, water, and pesticides. Furthermore, integrated smart farming systems enhance resilience to climate variability by enabling adaptive management strategies.

## **12. Future Prospects of Soil pH Monitoring Technologies**

The future of soil pH monitoring is rapidly evolving as agriculture transitions toward data-driven, technology-intensive systems that prioritize efficiency, sustainability, and resilience. With the global population continuing to expand, ensuring food security while minimizing environmental degradation has become a central challenge. Soil pH, being a fundamental determinant of nutrient availability and soil health, is expected to remain a critical parameter in next-generation agricultural management systems. Future developments in soil pH monitoring will focus on integrating advanced sensors, AI, and sustainable practices to enhance precision agriculture (Song et al., 2026; Reza et al., 2025). Innovations such as low-cost sensors, AI-driven analytics, and remote sensing technologies will improve accessibility and efficiency. Emerging innovations are converging at the interface of advanced sensing technologies, artificial intelligence, and sustainable farming practices. These developments are enabling more precise, real-time, and scalable monitoring of soil conditions, thereby supporting precision agriculture and resource optimization. The integration of digital technologies is expected to transform soil pH monitoring from a periodic, manual activity into a continuous, automated process embedded within broader smart farming ecosystems.

## **12.1 Development of Low-Cost and Accessible Sensors**

A major constraint in the widespread adoption of modern soil pH monitoring technologies is the high cost associated with advanced sensors and supporting infrastructure. This limitation is particularly pronounced in developing regions, where smallholder farmers often lack access to capital-intensive technologies. Consequently, future research is increasingly focused on designing affordable and accessible sensor systems without compromising accuracy and reliability. Innovations in material science are facilitating the development of low-cost sensing components, including biodegradable electrodes and flexible substrates that can be mass-produced at reduced costs. Miniaturization of sensors is another critical area of advancement, enabling the creation of portable, handheld devices that farmers can easily deploy in the field. Furthermore, user-friendly interfaces, often integrated with mobile applications, are being developed to simplify data interpretation and decision-making. Smartphone-based soil pH detection systems, which utilize imaging techniques and embedded sensors, are emerging as practical solutions for on-site analysis. These technologies have the potential to democratize soil monitoring, making it accessible to farmers with limited technical expertise and financial resources, thereby bridging the technological gap between developed and developing agricultural systems.

## **12.2 Integration with Artificial Intelligence and Big Data**

Artificial intelligence (AI) and big data analytics are poised to revolutionize soil pH monitoring by enabling predictive, adaptive, and automated decision-making processes. Traditional soil analysis methods are often reactive, relying on periodic measurements that may not capture dynamic changes in soil conditions. In contrast, AI-driven systems can process continuous streams of data from multiple sensors, identifying patterns and predicting future soil behavior with high accuracy. Machine learning algorithms can analyze historical and real-time data to forecast soil pH fluctuations, allowing farmers to take proactive measures to maintain optimal conditions for crop growth. These systems can also generate automated recommendations for fertilizer application, ensuring that nutrient inputs are precisely matched to soil requirements, thereby reducing waste and environmental impact. Additionally, AI can optimize irrigation schedules by integrating soil moisture, weather forecasts, and crop growth models, further enhancing resource efficiency. The role of big data is equally significant, as it enables the integration of diverse datasets, including soil properties, climatic variables, and crop performance metrics. This holistic approach facilitates more informed and context-specific decision-making, ultimately leading to improved agricultural productivity and sustainability.

## **12.3 Smart Farming and Automation**

The concept of smart farming represents a paradigm shift in agricultural practices, characterized by the integration of interconnected technologies that automate and optimize farm operations. Soil pH monitoring is becoming an integral component of these systems, contributing to the development of fully automated agricultural environments. In smart farming systems, soil sensors are linked with other technologies such as autonomous tractors, robotic planters, and smart irrigation systems. These interconnected devices communicate through centralized platforms, enabling coordinated and real-time responses to changing field conditions. For instance, if soil pH sensors detect suboptimal conditions, automated systems can adjust fertilizer application rates or initiate liming processes without human intervention. Robotic crop management systems can further enhance efficiency by performing tasks such as planting, weeding, and harvesting with precision. The integration of soil pH monitoring into these automated systems not only reduces labor requirements but also minimizes human error, leading to more consistent and reliable agricultural outcomes. As these technologies continue to advance, smart farming is expected to become increasingly accessible, transforming traditional agriculture into a highly efficient and technologically driven enterprise.

## **12.4 Remote and Satellite-Based Innovations**

Remote sensing technologies are playing an increasingly important role in soil monitoring by providing large-scale, non-invasive data collection capabilities. Advances in satellite imaging and drone-based monitoring are enabling the assessment of soil properties, including pH, over extensive agricultural landscapes. High-resolution satellite imagery can capture subtle variations in soil and crop conditions, which can be analyzed using sophisticated algorithms to infer soil pH levels. Similarly, unmanned aerial vehicles (UAVs) equipped with multispectral and hyperspectral sensors can provide detailed, field-level data with greater spatial and temporal resolution. Future developments in this domain are expected to focus on improving the accuracy and reliability

of remote sensing techniques, particularly through the integration of AI models that can enhance data interpretation. Real-time data processing is another critical area of innovation, allowing farmers to receive immediate insights and take timely actions. The combination of remote sensing with ground-based sensors will create comprehensive monitoring systems that offer both macro- and micro-level insights into soil conditions, thereby supporting more effective and efficient agricultural management.

### **12.5 Sustainable Agriculture and Climate Resilience**

Sustainability is a central objective in modern agriculture, and soil pH monitoring plays a vital role in achieving this goal. By enabling precise management of soil conditions, advanced monitoring technologies help reduce the excessive use of fertilizers, which is a major source of environmental pollution. Optimizing soil pH ensures that nutrients are efficiently utilized by crops, minimizing losses through leaching and runoff. This not only enhances crop productivity but also protects water resources and reduces greenhouse gas emissions associated with fertilizer production and application. Furthermore, maintaining optimal soil pH contributes to improved soil structure and microbial activity, which are essential for long-term soil health. Enhanced soil health, in turn, supports carbon sequestration, helping to mitigate climate change. As climate variability continues to pose challenges to agricultural systems, the ability to monitor and manage soil conditions in real time will be crucial for building resilient farming systems. Soil pH monitoring technologies, therefore, represent a key component of sustainable agriculture, enabling farmers to balance productivity with environmental stewardship.

## **13. Policy Implications and Global Perspectives**

The successful implementation of modern soil pH monitoring technologies depends not only on technological advancements but also on supportive policy frameworks and institutional involvement. Government support, research funding, and training programs are essential for promoting the adoption of soil monitoring technologies (Foley et al., 2011). Public-private partnerships and affordable solutions will facilitate adoption in developing countries (Cai et al., 2025). Governments, research organizations, and private sector stakeholders must collaborate to create an enabling environment that promotes innovation and adoption.

### **13.1 Role of Government and Institutions**

Governments and agricultural institutions play a pivotal role in facilitating the adoption of soil monitoring technologies. Financial support mechanisms, such as subsidies and incentives for precision agriculture tools, can significantly reduce the economic burden on farmers. Investment in research and development is essential for advancing sensor technologies and improving their affordability and performance. Additionally, capacity-building initiatives, including training programs and extension services, are crucial for equipping farmers with the knowledge and skills required to effectively use these technologies. By fostering collaboration between academia, industry, and farming communities, institutions can accelerate the development and dissemination of innovative solutions.

### **13.2 Adoption in Developing Countries**

In developing regions, the adoption of advanced soil monitoring technologies is often hindered by economic, infrastructural, and educational constraints. Smallholder farmers, who constitute a large proportion of the agricultural workforce, may lack access to modern tools and technical expertise. To address these challenges, strategies must focus on developing cost-effective technologies tailored to local conditions. Community-based training programs can play a significant role in enhancing awareness and building technical capacity. Public-private partnerships can also facilitate the distribution of affordable technologies and support services. By adopting inclusive and context-specific approaches, it is possible to ensure that the benefits of modern soil pH monitoring technologies are accessible to farmers across diverse socio-economic settings.

### **13.3 Contribution to Global Food Security**

Efficient soil management is fundamental to achieving global food security, particularly in the face of increasing population pressure and climate change. Soil pH monitoring contributes to this objective by enabling more precise and efficient use of agricultural inputs, thereby increasing crop productivity. By reducing resource

wastage and improving nutrient use efficiency, these technologies support sustainable intensification of agriculture. This approach allows for higher yields without expanding agricultural land, thereby preserving natural ecosystems. As a result, soil pH monitoring technologies are not only tools for improving farm-level productivity but also essential components of global strategies aimed at ensuring food security and environmental sustainability.

## **14. Limitations and Research Gaps**

Despite advancements, challenges such as sensor calibration, data management, and high costs remain (Kumar et al., 2015). Future research should focus on improving sensor accuracy, developing standardized methods, and integrating multidisciplinary approaches (McBratney et al., 2005).

### **14.1 Technical Limitations**

Technical challenges continue to affect the performance and reliability of soil sensors. Calibration issues are a major concern, as sensors may produce inaccurate readings if not properly calibrated for specific soil conditions. Additionally, the durability of sensors in harsh environmental conditions, such as extreme temperatures and moisture levels, remains a limitation. Soil heterogeneity further complicates measurement accuracy, as variations in soil composition can influence sensor readings.

### **14.2 Data Management Challenges**

The increasing use of sensor networks and digital technologies has led to the generation of large volumes of data, presenting significant data management challenges. Efficient storage, processing, and analysis of these datasets require advanced computational infrastructure and expertise. Ensuring data accuracy and reliability is also critical, as errors in data can lead to incorrect decision-making. Integrating data from multiple sources, including sensors, satellites, and weather stations, adds another layer of complexity.

### **14.3 Economic Constraints**

Economic factors remain a major barrier to the adoption of advanced soil monitoring technologies. High initial investment costs, coupled with maintenance and operational expenses, can deter farmers from adopting these systems. Limited access to financial resources and credit facilities further exacerbates this issue, particularly in rural areas.

### **14.4 Research Gaps**

Future research should focus on addressing these challenges through the development of standardized calibration methods that can be applied across different soil types and environmental conditions. Improving sensor accuracy and durability is essential for enhancing reliability and user confidence. Additionally, there is a need for multidisciplinary approaches that integrate soil science, engineering, data analytics, and socio-economic considerations. Such approaches will enable the development of holistic solutions that are both technically effective and economically viable.

## **15. Comprehensive Discussion**

The integration of modern soil pH monitoring technologies into agricultural systems represents a paradigm shift in crop management. The transition from conventional methods to advanced sensing technologies has enabled farmers to adopt data-driven approaches, leading to improved productivity and sustainability. The integration of advanced soil monitoring technologies with AI and IoT has transformed agriculture into a data-driven system, improving productivity and sustainability (Gebbers & Adamchuk, 2010). However, addressing economic and technical barriers is essential for widespread adoption.

Electrochemical sensors remain the most widely used due to their accuracy, but they require frequent calibration. Spectroscopic techniques offer rapid and non-destructive analysis but depend heavily on calibration models. Proximal and remote sensing technologies provide spatial insights, while IoT-based systems enable

real-time monitoring. The combination of these technologies with artificial intelligence has further enhanced their capabilities, allowing for predictive modeling and automated decision-making. This integration is particularly beneficial in addressing challenges such as climate variability and resource scarcity. Case studies across different regions demonstrate that the adoption of soil pH monitoring technologies leads to significant improvements in crop yield, resource efficiency, and environmental sustainability. However, the widespread adoption of these technologies requires addressing economic and technical barriers.

## 16. Conclusion

Soil pH is a fundamental factor influencing soil health, nutrient availability, and crop productivity. Modern soil pH monitoring technologies have revolutionized agricultural practices by providing real-time, high-resolution data that enables precise soil management. This review highlights the advancements in soil pH sensing technologies, including electrochemical sensors, spectroscopic methods, proximal and remote sensing, and IoT-based systems. The integration of these technologies with artificial intelligence and big data analytics has further enhanced their effectiveness. The relationship between soil pH and crop yield is well-established, and maintaining optimal pH levels is essential for maximizing productivity. Case studies demonstrate that precision soil pH management can significantly improve crop yield while reducing input costs and environmental impacts. Despite these advancements, challenges such as cost, technical complexity, and environmental variability must be addressed to ensure widespread adoption. Future research should focus on developing affordable and robust technologies, improving data integration, and promoting sustainable agricultural practices. In conclusion, modern soil pH monitoring technologies play a crucial role in achieving sustainable agriculture and ensuring global food security. Their continued development and adoption will be essential in meeting the challenges of the future.

## 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 they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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