# Use of Probes and Sensors in Agriculture—Current Trends and Future Prospects on Intelligent Monitoring of Soil Moisture and Nutrients

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*Review*

# Use of Probes and Sensors in Agriculture—Current Trends and Future Prospects on Intelligent Monitoring of Soil Moisture and Nutrients

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**Abstract:** Soil monitoring is essential for promoting sustainability in agriculture, as it helps prevent degradation and optimize the use of natural resources. The introduction of innovative technologies, such as low-cost sensors and intelligent systems, enables the acquisition of real-time data on soil health, increasing productivity and product quality while reducing waste and environmental impact. This study examines various agricultural monitoring technologies, focusing on soil moisture sensors and nutrient detection, along with examples of IoT-based systems. The main characteristics of these technologies are analyzed, providing an overview of their effectiveness and the key differences among various tools for optimizing agricultural management. The aim of the review is to support an informed choice of the most appropriate sensors and technologies, thus contributing to the promotion of sustainable agricultural practices.

**Keywords:** smart farming; proximal sensing; soil monitoring; low cost

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## 1. Introduction

Soil exploitation, pollution, and climate change have had severe consequences on the quality and productivity of agricultural land. These interacting factors contribute to soil degradation and sterility. Since its biophysical functions are responsible for nutrient cycling and water dynamics and support crop growth [1], soil quality control is of fundamental importance to prevent its degradation and ensure optimal productivity. The agricultural sector is responsible for 70% of global water consumption [2], thereby exacerbating the growing crisis of water scarcity worldwide [3]. Beyond the high usage of water resources, agriculture also has a substantial impact on GHG emissions, contributing between 19% and 29% of global annual emissions [4]. Additionally, with the global population projected to reach 10 billion by 2050 [5], there is an anticipated increase in the demand for higher-quality food. These pressures highlight the urgent need to adopt innovative and sustainable agricultural strategies aimed at promoting effective soil monitoring, ensuring food security, and reducing environmental impact. Soil quality is determined through the monitoring of its characteristics. Electrical conductivity and dielectric properties provide information about nutrient content and moisture levels, respectively. Since these parameters are related to fertility and are essential for optimizing crop yields [6], the monitoring focuses on measuring and controlling these indicators. Soil monitoring techniques range from conventional methods to more recent and technological approaches. Conventional methods consist of laboratory analyses. These are extremely accurate but involve the destruction of samples, high costs, and long timescale, making them limited for large-scale use. Innovative methods leverage the potential of remote sensing and proximal sensing. Remote sensing uses satellite and drone imagery to facilitate the monitoring of large areas in high resolution.

Nowadays, remote sensing is an effective method for obtaining useful information on soil health and crop growth; however, it does not provide real-time information. Satellite images are studied to develop predictive models for estimating soil quality indicators such as salinity, nutrients, and moisture [7–9]. Integrated multi- or hyperspectral sensor UAV systems present encouraging and promising aspects for plant disease detection and pest monitoring [10,11]. Proximal sensing involves the use of various technologies and sensors, which are useful for monitoring agro-meteorological conditions and soil characteristics. Proximal sensors collect data from the soil when the detector is in direct contact with it or in close proximity, providing information based on physical measurements that are related to the soil's properties [12]. The accessibility of low-cost sensors and components, combined with advanced technologies, has encouraged the implementation of intelligent monitoring systems. These systems, which fall under the concept of smart farming, rely on data collection and analysis, providing a more accurate monitoring of soil conditions. This enables farmers to make informed decisions and optimize agricultural practices, thereby contributing to preserving natural resources and mitigating climate change. A smart irrigation management and monitoring system has been developed, allowing for autonomous and optimized water distribution. The system utilizes low-cost automatic sensors that detect soil moisture and plant health in real time [13]. An IoT-based drip irrigation system has been implemented to continuously monitor environmental conditions, soil moisture, and temperature levels. The integrated sensors send data to microcontroller, which processes the information and initiates irrigation if necessary [14]. Such systems allow for precise and automated irrigation regulation based on the crops' actual water needs. This enables plants to grow and develop optimally, preventing the risk of water stress or over-irrigation and promoting healthier, more vigorous and productive crops. Traditional irrigation systems tend to cause over-irrigation, with negative effects on crops such as slowed growth, wilting and yellowing of leaves, and increased vulnerability to molds and pathogens [15,16]. This occurs because, lacking precise control, traditional systems often supply excessive amounts of water, thereby disrupting the soil's water balance. In contrast, modern systems allow for the maintenance of optimal soil moisture levels, enabling more targeted and efficient irrigation. This promotes the rapid development and uniform growth of crops, with greener leaves and more fruits that tend to ripen earlier compared to those produced with traditional systems [16]. From soil monitoring, it is possible to identify areas of similar quality, called Management Unit Zones (MUZs), which are important for the planning and adoption of appropriate and precise soil management programs according to specific characteristics [7,17]. By knowing and monitoring the concentration of soil nutrients, the efficient use of fertilizers is enabled, avoiding deficiencies or excesses that could reduce productivity. An autonomous fertirrigation system is proposed, based on a wireless sensor network and equipped with a photovoltaic panel. This system monitors real-time weather conditions, soil moisture, and plant health. It integrates the collected data with a crop-specific database [18]. Implementing these solutions allows for the efficient use of water and fertilizers, which helps with environmental sustainability and leads to significant cost and waste reduction. The use of automated systems can save approximately 50% of resources [19,20] resulting in an economic savings of EUR 450/ha [21]. These aspects highlight how precision agriculture represents a management strategy that offers multiple long-term benefits, including reduced yield variability, improved environmental performance, and significant economic returns [22]. Nevertheless, its implementation and components present some critical elements that must be considered and overcome. The response and reliability of sensors and monitoring systems can be affected by various soil properties, including texture, bulk density, and environmental factors. It has been shown that the performance of various types of sensors is significantly influenced by the composition and structure of the soil. Devices such as the TDR and the Hydraprobe, the latter of which measures electrical conductivity, tend to underestimate soil moisture levels [23]. Sensors measuring the dielectric constant have a fairly linear response to moisture but can also be influenced by the presence of silt, clay, and sand in the soil [24]. Therefore, to reduce measurement errors and improve accuracy, it is necessary to develop specific calibration formulas for each type of sensor and the specific soil type on which they are used [23]. Monitoring systems face significant challenges, particularly regarding connectivity, power supply, and data transmission, due to the lack of infrastructure, services, and internet access, especially in rural areas. Numerous researchers have developed effective solutions to ensure the continuous and accurate operation of these systems, even in the absence of cellular networks. To address this lack, researchers [25–27] propose monitoring systems using LoRa technology, which enables real-time data transmission over long distances (5–15 km) with low energy consumption [25]. In addition, LoRa technology ensures continuous monitoring at a low cost [26]. The lack of access to electrical supply has promoted the development of energy-autonomous systems for continuous monitoring. The system proposed in the following study [28] involves the use of long-lasting lithium batteries and small photovoltaic panels on individual sensor nodes, intended for soil health monitoring. The system is characterized by good energy efficiency and is capable of operating completely autonomously for an extended period. The authors [27] have implemented a monitoring system based on LoRa technology, equipped with a solar panel for collection and conversion into electricity, successfully powering the entire system and recharging the battery, with residual energy available. An innovative water monitoring system is described in [29], powered by a battery and self-sustained through a hybrid solar-hydroelectric energy collection system. The system uses a photovoltaic panel and a hydroelectric microgenerator, which together ensure optimized energy consumption and allow the system to operate continuously for approximately 432 h. These factors represent significant limitations for these systems, highlighting the need for particular attention from the scientific community. To overcome these challenges, it is essential to ensure operation even in disadvantaged areas while simultaneously enhancing the effectiveness and precision of the suggested solutions. The main proximal sensor technologies will be examined for monitoring soil moisture and nutrients. The aim of this study is to identify improvements in the performance and implementation of these sensors, as well as to highlight the critical challenges that must be addressed to optimize the effectiveness of soil monitoring.

The text is organized as follows: the introduction provides an overview of the need to adopt innovative and sustainable systems, such as IoT systems. It presents some recently developed low-cost systems, focusing on the main challenges to be addressed, particularly in disadvantaged areas. Section 2 analyzes the main technologies used in soil moisture monitoring systems. Section 3 focuses on the technologies employed for monitoring soil nutrients. Section 4 explores the implementation of IoT systems and the various associated communication technologies. Finally, Section 5 presents the conclusions and outlines future directions to improve the reliability of monitoring systems.

## 2. Soil Moisture Monitoring Technologies

The control and monitoring of soil-water concentration are essential to help farmers manage irrigation efficiently. Moisture, in addition to influencing the physical characteristics of the soil, is essential for the transport and dissolution of nutrients, making it crucial for crop survival and soil fertility [30]. Soil water exists in two forms: bound and unbound. Bound water refers to the portion adsorbed by soil mineral particles, making it unavailable and unabsorbed by plant roots [31]. In contrast, unbound water refers to water molecules that move freely in the soil and it is available to plants, defined as soil water content (SWC) [31], and expressed either as gravimetric water content (GWC) (Equation (1)) or volumetric water content (VWC) (Equation (2)), according to the formulas [31]:

$$GWC = \frac{m\ wet - m\ dry}{m\ dry} \tag{1}$$

$$VWC = GWC * \frac{\rho soil}{\rho water} \tag{2}$$

where mwet represents the mass of soil sample collect; mdry is the mass of dried soil; $\rho$soil is bulk density of soil; $\rho$water is the density of water, usually taken to be 1000 kg/m$^3$ [31].

Direct methods for determining moisture involve the destruction of the sample and prolonged processing times. Gravimetric determination, although very accurate, is now less common as it does not lend itself to the automation of irrigation processes while still playing a fundamental role in sensor calibration. Indirect methods measure soil moisture content by monitoring its physical or chemical properties. Among these are various techniques that enable the efficient management of automated irrigation, which will be discussed in more detail later. However, there are many factors that directly and indirectly influence the distribution of water, including land use, cover, pedology, and climatologic properties [32]. Solar radiation and ambient temperature have an indirect influence on moisture content, as they alter soil temperature and humidity. Evapotranspiration and precipitation, on the other hand, directly affect moisture levels, decreasing it through evapotranspiration or increasing it in the case of precipitation [33]. The structure, texture, and slope of the soil influence water infiltration and drainage: sloped soils allow water to move downward and drain more quickly compared to flat areas [34]. Just as texture affects water drainage in soil, sandy soils with finer textures, like clay, will have lower drainage compared to coarser-textured soils with a high sand content [33]. Knowing the characteristics of the soil, the crops, and the technologies of monitoring systems is essential for implementing reliable monitoring systems that address the field's specific conditions and the farmers' particular needs.

This section describes the main moisture sensing technologies used in intelligent monitoring systems, illustrating the principle of the operation of the sensors and providing examples of recently implemented systems. Additionally, the main strengths and weaknesses will be highlighted to better understand the potential, allowing for guidance toward selecting the most appropriate technology.

### 2.1. Tensiometers

The tensiometer measures the matric potential of the soil or the water tension present in the soil. They are made up of a tube with distiller water, a porous ceramic tip attached to the lower end a vacuum gauge, acting as a pressure meter, located at the upper back [35] (see Figure 1). The measurement principle is simple and works in 0–1 intervals [33]. First, the ceramic tip must be placed at the optimal depth and have good contact with the soil to ensure an accurate reading and avoid errors [36]. If the soil is in a saturated condition, an equilibrium will be established between the water in the soil and that in the tube, causing the gauge to indicate a pressure close to atmospheric pressure, tending to 0 [35]. When the soil moisture changes, water is either absorbed or released through the ceramic tip. If the soil moisture is low, water is released from the tube, creating a vacuum inside and generating negative pressure. Conversely, when moisture increases, the vacuum decreases, and the gauge will register positive pressure [36]. These tools are easy to use and cost-effective, with performance unaffected by ambient temperature or soil salinity.

However, they do require specific attention, such as the regular refilling of the tube with water and periodic maintenance to prevent cavitation issues [37]. The authors [37] propose a self-refilling system for the METER T-8 tensiometer, utilizing two solenoid valves connected to the sides of the circuit. The inlet is connected to a 3 L water reservoir. This system, with a relatively low cost (around USD 100), significantly reduces the need for manual refilling, making it especially useful in arid and dry areas where this process needs to be performed more frequently. An affordable IoT tensiometer (USD 76) for measuring soil-water potential has been proposed [35]. It uses an isolated BMP180 barometric sensor connected to an ESP32 microcontroller, which allows for vacuum tension measurements every 6 h. The tensiometer provides high precision in measuring soil-water potential ($R^2$ = 0.99) down to $-80$ kPa. Additionally, the prototype is powered by a lithium battery recharged via a solar panel, and, thanks to the deep sleep function, the system is energy autonomous. Data are uploaded to a ThingSpeak platform, where it can be viewed online as a soil-water potential curve. Manufacturer companies such as Ecosearch and Irrometer offer a wide range of commercial tensiometers, ranging from traditional systems to electronic and IoT models, with relatively affordable costs starting from USD 60 to USD 80 and up [38,39]. Among these, the "Full Range" dry tensiometer produced by Ecosearch Srl (Montone, Italy) stands out. This tensiometer, unlike traditional water-filled models, is capable of measuring soil tension up to 5–15 bar [38], as well as soil temperature. Its operating principle is based on applying a known pressure within the measurement chamber, which is reduced by soil tension; thus, rather than indirectly measuring water tension, it provides a direct measurement of pressure. A summary of the characteristics of the tensiometers is provided in Table 1.

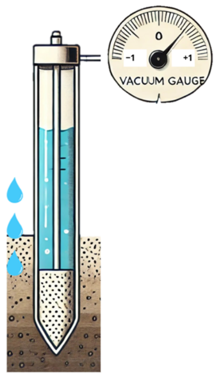


**Figure 1.** Schematic of a tensiometer's operation in the soil. This instrument, composed of a tube filled with distilled water and a porous ceramic tip, measures the matric potential of the soil. The pressure reading, taken with a vacuum gauge, varies with soil moisture: under saturated conditions, pressure approaches zero, while moisture changes result in negative or positive pressures based on water release or absorption (OpenAI, (2024)).

**Table 1.** The table presents tensiometers, highlighting their operating principle, strengths, and weaknesses.

| Type Sensor | Operating Principle | Strengths | Weakness |
| --- | --- | --- | --- |
| Tensiometers | Measurement of soil matrix potential. Working temperature 10–45 °C. | - Affordable.<br>- Simple.<br>- Unaffected by temperature and salinity. | - Frequent maintenance.<br>- Long stabilization times required once placed in the soil (from a few minutes to hours).<br>- Not recommended for sandy soils. |

*2.2. Granular Matrix Sensor*

Granular matrix sensors are electrical resistance sensors used to measure soil tension, as shown in Figure 2. The sensor consists of a pair of electrodes embedded in a gypsum block, either cylindrical or rectangular in shape, which is inserted directly into the soil [36]. The sensor transmits a current through the porous medium, with the system's electrical resistance varying proportionally to the amount of water absorbed [40]. When a small voltage is applied to the sensor, it produces a voltage proportional to the resistance of the block. When the soil is moist, water is absorbed by the gypsum, seeking to equilibrate with the soil's moisture. This results in a decrease in the resistance of the electrodes [36].

**Figure 2.** Granular matrix sensor, composed of a pair of electrodes embedded in a gypsum block.

The sensor can provide the matrix potential value using a specific calibration equation. One of the most common commercial granular matrix sensors is the WATERMARK, produced by Irrometer Company, Inc., Riverside, CA, USA. The Watermark sensor consists of a pair of corrosion-resistant electrodes immersed in a granular matrix that equilibrates with the surrounding soil moisture, providing a reliable measurement of soil-water tension in centibars or kPa [39]. This sensor is widely used in irrigation planning due to its ability to provide accurate data, and it can be read manually or be connected to a data logger for remote monitoring. The effective performance of the Watermark sensor was tested in the study [41]. The system worked well, but a response delay was observed under drought and high humidity conditions. Another significant finding from the study is that the sensor at shallow depths does not provide reliable readings, whereas installations at depths greater than 30 cm proved to be more effective. Additionally, specific calibration for each soil type is necessary to ensure reliable readings. These aspects are confirmed by [42]. Soil-specific calibration improved the accuracy of the sensor; however, the Watermark tends to underestimate moisture levels in coarse-textured soils and when installed at shallow depths. Granular matrix sensors are cost-effective, with prices ranging from USD 60 to USD 300 [39], depending on the size of the sensor and whether an additional data logger for remote monitoring is included. They do not require significant maintenance; however, the strength of gypsum is affected by temperature and tends to dissolve over time. Moreover, the systems requires specific calibration for different soil types because the accuracy is rather poor and can vary widely, between 10% and 25% of the actual measurement [40]. The main characteristics of the Watermark sensor are summarized in Table 2.

**Table 2.** The table presents the main characteristics of granular matrix sensors used for measuring soil moisture.

| Sensor Type | Operating Principle | Strengths | Weakness |
|---|---|---|---|
| Granular matrix sensors | Measurement of soil tension, exploiting the change in resistance of the porous section in the soil. Measuring range: 0 to 200 kPa. | - Easy to use and inexpensive.<br>- Low maintenance.<br>- Good response to soil moisture variations. | - Low accuracy.<br>- Slow response.<br>- Gypsum dissolution.<br>- Influence of T on gypsum strength.<br>- Installation in the surface layers of the soil does not provide reliable results.<br>- Underestimated value in coarse-textured soils. |

### *2.3. Thermal Probe*

Thermal probes, for determining soil moisture, utilize heat dissipation, measuring the temperature of a porous block or the soil, after the application of a thermal pulse [31]. The basic components of this type of sensor are a thermistor, which serves as a heat source, and a temperature sensor, both embedded in a porous block (made of gypsum or ceramic) and buried in the soil [31]. Heat dissipation sensors exploit the dependence of soil thermal conductivity on temperature and water content [43]. By applying a controlled heat pulse, the maximum temperature increase detected can be correlated to the volumetric water content of the soil [43]. Therefore, these systems relate the measured temperature to the conductivity of the material to obtain an accurate estimate of soil moisture. These can be of different implementations, the characteristics of which are summarized in Table 3.

**Table 3.** The table compares different thermal probe technologies (SPHP and DPHP) for estimating soil moisture, focusing on low-cost models.

| Sensor Type | Characteristics | Strengths | Weakness |
|---|---|---|---|
| Thermal probe | They exploit the soil's thermal conductivity to estimate moisture based on heat dissipation. | - Low-cost sensor.<br>- Temperature measurement.<br>- Long life.<br>- Maintenance-free.<br>- Easy implementation. | - Thermal conductivity is influenced by proprieties of the soil, as well as by the content of organic matter. |
| Single-probe heat pulse (SPHP) | Uses a single component as a heat source and temperature sensor. | - Low cost.<br>- High sensitivity. | - Few implementations. |
| Double-probe heat pulse sensor (DPHP) | Component separate. | - Low power.<br>- Accurate sensor.<br>- Cheap.<br>- Easy implementation. | - Calibration for each soil type.<br>- Affected by temperature and environment humidity. |
| Multi-probe heat pulse sensor (MPHP) | Separate components and multiple temperature sensors. | - Accurate sensor. | - Calibration for each soil type.<br>- Affected by temperature and environment humidity. |

A single-probe heat pulse sensor (SPHP) is implemented by [44], consisting of a single element: a bipolar transistor. This transistor acts as a heat source through the base-collector junction, while the base-emitter junction serves as the temperature sensing system. Subsequently, the system is incorporated into a porous capsule, which prevents direct contact with the soil, reducing potential interference and improving accuracy [45]. This encapsulation gives the system greater sensitivity in measurements, thus highlighting its potential as a soil moisture sensor. A single-element SHPP system is implemented using nanocrystallized materials [46], both as a heat source and a temperature sensor. This technology offers superior sensitivity in measurements compared to previously described systems, making it particularly appealing for moisture monitoring. Additionally, the system is integrated with a microcontroller featuring a Bluetooth module, enabling easy and fast data transmission to mobile devices. Single-probe systems offer numerous advantages for soil moisture determination, including greater sensitivity, especially due to materials highly reactive to moisture changes, such as nanocrystals. Their simple design is based on a single element, making them more compact, less bulky, and low cost. However, there are still few studies in the literature on these technologies, and further research and development are needed, especially for implantation in the field. Double-probe heat pulse (DPHP) sensors feature a heat source and a temperature sensor on two separate probes. In the system proposed by [47] in 2015, the heating element consists of a bent copper wire, designed to increase resistance, enclosed in a steel tube. Meanwhile, a thermocouple is placed on the probe located 3 mm away to serve as the temperature sensor. This DPHP system is low power, powered by lithium batteries and equipped with solar cells for recharging. It is a low-cost solution that offers good measurement reliability. However, a dependency between the measured moisture value and soil density, as well as ambient temperature, has been observed. Therefore, specific calibration that accounts for these factors is essential [47]. These systems can also be configured in a multi-probe setup. A prototype was presented by [43] in 2019, which featured multiple temperature sensors arranged around the heating probe on a planar PCB platform. During the study, the sensor demonstrated reliability in measurements, successfully detecting VWC ranging from 5% to 41% with a sensitivity of 0.632 °C for each 1% change in VWC [43].

Among commercial sensors, Campbell Scientific offers a heat dissipation matric potential sensor that measures soil-water potential from −10 to −2500 kPa [48]. Comprising a heating element and a thermocouple embedded in resin within a porous ceramic matrix, the sensor applies a current of 50 mA and measures the temperature increase, which varies based on the water content in the ceramic matrix, influenced by the moisture in the surrounding soil [48]. Generally, these types of commercial sensors require specific soil calibration, are affected by environmental conditions (T and humidity), consume a lot of energy, and have a relatively low accuracy 5–10% [49].

### *2.4. Capacitive Sensor*

Capacitive sensors are among the main tools used in low-cost systems for determining the VWC in soil and implementing smart irrigation systems. The probe is shown in Figure 3. They are characterized by their affordability and ease of implementation, and, after appropriate soil-specific calibrations, they provide high accuracy and reliability. They consist of electrodes that function as capacitors, with a hygroscopic material between them; in particular, the soil surrounding the electrodes is a dielectric medium that stores the charge [50]. Capacitive sensors exploit the difference between the dielectric constant of dry soil, $\varepsilon_{soil}$ = 2–6, and that of water, which is significantly higher, $\varepsilon_{water}$ = 80, at 20 °C [51]. Consequently, the dielectric properties of the soil depend on its moisture content, and its value varies according to the volumetric water content [52]. The capacitive sensor utilizes this property and emits a voltage, the inverse of which can be linearly adjusted to estimate the soil's volumetric water content through gravimetric methods [51].

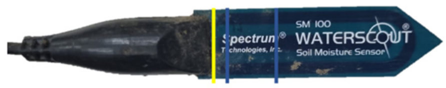


**Figure 3.** The photo shows a low-cost capacitive probe designed for soil moisture measurement. The yellow line indicates the "warning line", which marks the part of the sensor that should not be inserted into the soil, while the area between the blue lines identifies the recommended depths for proper insertion into the soil.

This sensor type is known for its affordability and accuracy in readings. It allows for quick and continuous measurements, requiring minimal maintenance after installation. These advantages have sparked significant interest from scholars and researchers, making them one of the most widely used sensors in soil moisture monitoring systems. However, their performance and accuracy are significantly influenced by soil texture and composition, ambient temperature, and the frequency of the alternating current used for measurements, necessitating specific calibrations, the performance and accuracy of such systems are highly influenced by soil composition, ambient temperature, and the frequency of the alternating current used for measurement [51,53,54]. Considering the low cost and ease of implementation, several studies have focused on the development and validation of capacitive sensors for soil moisture monitoring. The solution proposed by Farm21 (Amsterdam, The Netherlands) is easy to install (30 s), factory-calibrated, and maintenance-free. It includes a soil moisture probe (FS21, manufactured by Farm21) and a weather station [55], providing precise data on air humidity and temperature, soil moisture, and soil temperature at varying depths, from 10 to 20 cm for temperature and 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm depth for moisture [55]. The system has a rechargeable battery via USB-C that consumes little power, lasting up to a year on a single charge, and is also included in the Farm21 platform that also provides satellite imagery, scouting, and weather. The initial cost is EUR 295 per sensor, to which is added a cost of EUR 63/sensor/year for connectivity (2G/LTE-M/NB-IoT SIM card provided by Farm21), support, and data storage. It is a robust and reliable system for monitoring and optimizing irrigation and fertilization for applications in broccoli, potato, and apple crops [55]. Several experts have focused on implementing cost-effective and reliable solutions to provide farmers with accurate and reliable evaluations, overcoming some of the major shortcomings of commercial systems. As an example of the development of generalized calibration equations relating the dielectric constant to soil properties and characteristics and possible solutions to sensor sensitivity to soil properties, several authors [56] highlight the higher accuracy of capacitive sensors compared to resistive sensors in determining moisture by means of the Spearman coefficient, which have $r_s$ = 0.93 and 0.87, respectively. Furthermore, accuracy and performance are improved in relation to the manufacturer's specifications through specific calibration. The simplicity and reliability of SKU: SEN0193 (DFRobot, Shanghai, China), has been studied and tested [57] for its potential use in automatic humidity monitoring. The proposed system has proven reliable in predicting water content for organic-rich soils and distinguishing three different levels of soil moisture: dry to moderately moist, field capacity, and saturated. However, the study shows significant sensor-to-sensor variability, of 5% for the four sensors SKU: SEN0193 used [57]. The authors [58] propose a solder mask plus acrylic paint as an effective solution to salt water interference, which is one of the main problems with dielectric techniques. The intelligent monitoring system consists of an air temperature and humidity sensor (DHT11 sensor), soil temperature sensor (DS18B20), and capacitive soil moisture sensor, manufactured in a workshop for electronic industries in Egypt; the power supply unit comprises 120 W-22 V-6 A photovoltaic panels. In the study, both sensor-to-sensor variability and variability in measurements and replications of the sensor response are recognized; however, the coefficient of the variation of such sensors is less than 25%, providing high performance in estimating moisture content in clay soils. Several authors [59] proposed an individual calibration per sensor as the best option, especially if it was supplied with low voltage; the 3.3 V option produced the best correlation between SWC and sensor output ($R^2$ = 0.871) compared to the 5.5 V option ($R^2$ = 0.798) [59]. The existence of a temperature dependence on the sensor response has also been demonstrated, although with minimal effects. For a change of 20 °C, there was a variation in water content of 0.015 $m^3/m^3$ [59]. Various low-cost capacitive probes are available on the market, with prices ranging from USD 2 to USD 15 per probe. This economic advantage has made it possible to develop remote monitoring systems, as these probes can be easily integrated with common microcontrollers like Arduino and ESP32 [14,16,28,60]. Thanks to this accessibility, it is possible to implement systems with multiple sensors, allowing for the coverage of large monitoring areas and resulting in more detailed and representative data, thereby enhancing the effectiveness of water resource management. The main characteristics of the described capacitive sensors are summarized in Table 4.

**Table 4.** The table compares and summarizes different capacitive sensor technologies for measuring soil moisture, highlighting their characteristics, strengths, and weaknesses.

| Sensor Type | Characteristics | Strengths | Weakness |
|---|---|---|---|
| Commercial capacitive sensor [55] | Measures the electrical capacity, i.e., the potential difference between two conductors to determine VWC. | - Provides real-time moisture change data.<br>- Large measuring range.<br>- Fast response.<br>- Chemical resistant.<br>- Small and compact.<br>- Low maintenance. | - Calibration.<br>- Strong influence of T.<br>- High costs and possible extra costs for assistance. |

**Table 4.** *Cont.*

| Sensor Type | Characteristics | Strengths | Weakness |
|---|---|---|---|
| SKU: SEN0193-Capacitive sensor [57] | | - Inexpensive prototype cost USD 45.7.<br>- Low operating current 5mV.<br>- Corrosion resistant. | - Specific soil calibration required.<br>- Variability between devices makes a specific calibration for each sensor appropriate.<br>- Sensitivity to the effects of salinity and soil structure. |
| Capacitive sensor [58] | Intelligent monitoring system with an operating frequency 430 kHz. | - High performance in moisture content estimation (CV < 25%).<br>- Accurate and robust system.<br>- Energy autonomy.<br>- Real-time monitoring of soil and environmental conditions.<br>- Salinity-insensitive probes. | - Variability between sensor and sensor; CV = 0.045 implies a specific calibration per sensor and soil type. |
| SKU: SEN0193-capacitive sensor [59] | | - System's ability to measure daily and seasonal humidity variations.<br>- Low voltage (3.3 to 5.5 V).<br>- Isolated system not sensitive to the presence of salts.<br>- Economic system (total cost USD 162.56).<br>- Minimal temperature dependence.<br>- Low energy consumption due to low-voltage operation that reduces energy demand by 40%. | - Medium accuracy.<br>- Individual calibration, requiring time and specialized labor.<br>- Low sampling volume.<br>- Sensitive to interference and short life expectancy. |

### *2.5. Time-Domain Reflectometry (TDR) and Frequency-Domain Reflectometry (FDR)*

TDR is an accurate and established measurement method for soil dielectric permittivity and moisture content. These consist of a transmission line, i.e., metal probes, placed in the soil, as shown in Figure 4. TDR sensors estimate the volumetric water content (VWC) by determining the bulk dielectric constant, K, of the soil through the measurement of the propagation time of an electromagnetic pulse along the sensor [61]. An average of the water content in the examined volume is therefore performed; therefore, such techniques do not give precise information on water content. These systems are characterized by their high accuracy, with precision within 1–2% of the volumetric water content [62], and they require minimal calibration. Additionally, they enable fast, simple, and continuous measurements, providing excellent spatial and temporal resolution [62]. It has become popular in soil-water content determination due to its simplicity, speed of acquisition, accuracy, and high resolution; it can be used up to a frequency of 1 GHz [63]. However, as well as the high initial costs, salinity affects the signal, causing a loss of reflection, and the increase in conductivity due to the rise in soil moisture is one of the main factors that makes these systems little used by farmers [63]. The authors [64] describe the TDR 20/20 sensor (supplied by AEA). This consists of two parallel probes for measuring the strength of soil with a predetermined volumetric water content. Good accuracy in determining the moisture content of sandy and clayey soils has been demonstrated. In particular, the TDR maintains its accuracy down to a water content of less than 30 per cent for clayey soils. As soil moisture increases, the sensor tends to overestimate moisture content, reducing performance accuracy. Other authors [65] attest to the effectiveness of the TDR-315L sensor in moisture determination for various soil types, using the factory calibration function.

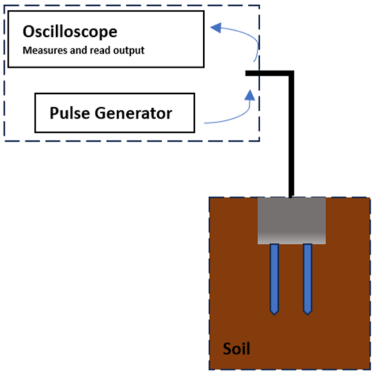


**Figure 4.** The image illustrates the principle of Time-Domain Reflectometry (TDR). A generator sends an electromagnetic pulse along a probe inserted into the soil, while the oscilloscope records the pulse reflection time. This measurement allows the calculation of the soil's dielectric constant, enabling the determination of the soil's water content.

Ecosearch (Montone, Italy) offers multiple solutions for soil studies, including several TDR sensors that are easy to use and available for limited budgets. The TDR 300 is a next-generation instrument that is portable and powered by AAA batteries. It offers the possibility of integrating a GPS to georeference points of measurement and interest. Data are stored by a data logger and easily viewed via the display on the instrument; this can be displayed as raw data, VWC and RWC. It offers precise calibrations for different soil types; however, high clay content, EC > 2 ds/m, and high organic content effect sensor performance and device reading [66].

FDR provides an estimation of soil moisture based on the variation in the frequency of a signal, which reflects the dielectric properties of the soil [67]. FDR probes are accurate methods for soil moisture measurements, presenting a good correlation ($R^2$ = 0.99) between moisture values estimated by FDR and values estimated by the gravimetric method [68]; in addition, more precise and accurate measurements are obtained after specific soil calibration ($\pm$0.01 $ft^3$ $ft^3$) [67]. These systems have various applications in agriculture [69–71], but the high costs, the demand for specialized personnel, and the sensitivity of sensors to influences make such systems uncommon. The main disadvantage of FDRs is temperature sensitivity: they tend to overestimate soil moisture with increasing temperature [72], but it is possible to significantly reduce measurement errors and improve measurement accuracy through specific calibration, considering the impact of temperature as proposed by [72]. The performance and response of the sensor can vary based on the type of sensor and substrate, bulk density, electrical conductivity (EC), and soil temperature. Therefore, it is essential to consider these factors during the calibration phase [73–75]. The advantages and disadvantages of TDR and FDR are summarized in Table 5.

**Table 5.** The table compares two sensor technologies for measuring soil moisture: Time-Domain Reflectometry (TDR) and Frequency-Domain Reflectometry (FDR).

| Sensor Type | Characteristics | Strengths | Weakness |
|---|---|---|---|
| TDR | The TDR sends an electromagnetic pulse along a probe inserted into the soil. It measures the time of reflection of the pulse to calculate the dielectric constant of the soil, which is influenced by the water content. | - High accuracy (within 1–2% of volumetric water content).<br>- Minimal calibration requirements<br>- Fast, continuous, and precise measurements<br>- Excellent spatial and temporal resolution. | - High initial costs, exceeding USD 100 per sensor.<br>- Sensitivity to soil salinity, which can cause loss of signal reflection.<br>- May require complex equipment and a solid technical understanding for installation and use. |

**Table 5.** *Cont.*

| Sensor Type | Characteristics | Strengths | Weakness |
| --- | --- | --- | --- |
| FDR | Measures soil moisture through the variation in the frequency of a signal that reflects the dielectric properties of the soil. | - Rapid and continuous measurements.<br>- Low maintenance.<br>- Good accuracy when properly calibrated. | - Sensitive to soil salinity and temperature.<br>- Requires specific calibrations for different soil types.<br>- Lower accuracy compared to TDR in certain applications. |

### 2.6. Cosmic Ray Neutron Sensor (CRNS)

These are among the most accurate tools for determining soil moisture, particularly utilizing the properties of hydrogen nuclei present in water. Through thermalization, a dispersion or slowing of these nuclei is induced [31], enabling the precise measurement of moisture content. They consist of a neutron source connected to a detector. When neutrons are released from the radioactive source, they disperse into the soil and collide with hydrogen atoms they encounter, causing a change in their speed. The detector then measures the density of thermalized neutrons in the system, allowing for an accurate assessment of soil moisture content [31]. It has been demonstrated that, through careful calibration, it is possible to achieve an accuracy of 0.02 in VWC [36], making them reliable and precise tools for monitoring soil moisture. The suitability of this technique for the implementation of automated irrigation systems has been evaluated, as it has many advantages over other methods. This is a non-invasive and easy-to-use method; in addition, the neutrons integrate naturally in an area with a radius of about 150 m and a depth typically of 2–4 dm [76], allowing an assessment of soil moisture distribution at different depths and offering a representative moisture measurement of a large area. The measurement can take place by means of stationary or itinerant CRNS. The first provides average SWC measurements on a hectare scale, ensuring continuity without the need for maintenance over time. In contrast, the vehicle-mounted CRNS can reveal spatial patterns of SWC on a mean scale but only on survey days [77]. In their work, the authors [78] show the good roving capability of CRNS, proposing a mobile system for the continuous monitoring of SWC on larger scales and at different depths. However, its technical implementation, data processing, and interpretation are complex [77]. They are also versatile and reliable tools for obtaining a high spatial resolution mapping of soil surface moisture by aerial over flight, as proposed by GNSS-R measurements were taken, and using the proposed model, moisture maps were created with a spatial resolution of 100 m, illustrating large differences between irrigated and non-irrigated areas, with good accuracy, an RMSE of 0.07 $m^3/m^3$. The advantages and disadvantages of CRNS are summarized in Table 6.

**Table 6.** The table compares two sensors for measuring soil moisture, CRNS and the Finapp Probe, outlining their main characteristics, advantages, and weaknesses.

| Sensor Type | Characteristics | Strengths | Weakness |
| --- | --- | --- | --- |
| CRNS | It uses a radioactive source and measures soil moisture by exploiting the properties of hydrogen nuclei; the neutrons collide with hydrogen atoms, changing their speed. | - Efficient, fast, and reproducible. High accuracy, better ±0.02 in volumetric water content, with correct calibration.<br>- Non-invasive. | - Radiation hazard.<br>- Skilled operators.<br>- Laborious and expensive method.<br>- Long calibration times. |
| FinApp Probe (FinApp start-up, Pavpva) [48] | Uses CRNS technology for soil moisture measurement. | - Non-invasive.<br>- Large-scale measurement (1–20 ha).<br>- Independence from soil properties.<br>- No calibration, easy to use and install.<br>- Compact and lightweight instrument.<br>- Obtaining detailed soil moisture maps.<br>- Decision support for irrigation. | - The sensor is unable to control irrigation. |

This section provided an analysis of various low-cost soil moisture monitoring systems, emphasizing their crucial role in agricultural irrigation management. The different sensor technologies discussed—including tensiometers, granular matrix sensors, thermal probes, capacitive sensors, Time-Domain Reflectometry (TDR), Frequency-Domain Reflectometry (FDR), and neutron moisture sensors—each offer distinct principles, components, advantages, and limitations. Tensiometers effectively measure soil matrix potential, while granular matrix sensors utilize electrical resistance to assess water tension. Thermal probes and capacitive sensors provide alternative methods for evaluating moisture content, with capacitive sensors known for their high accuracy and ease of use following calibration. TDR and FDR are well-established techniques that offer precise soil moisture measurements, although TDR is often associated with higher costs. Neutron moisture sensors stand out for their non-invasive capabilities, allowing extensive assessments of soil moisture distribution over larger areas. Each sensor type has unique characteristics, making them particularly suitable for specific agricultural applications. In conclusion, these low-cost soil moisture monitoring solutions are essential for improving irrigation efficiency. By enabling the real-time monitoring of soil moisture levels, they play a crucial role in optimizing water resource management and promoting sustainable agricultural practices. As technology advances, these systems will become increasingly accessible and effective, further supporting farmers in their efforts to maximize productivity and avoid the depletion of water resources.

## 3. Soil Nutrient Monitoring Technologies

It is well known that monitoring humidity and temperature is crucial for an optimal irrigation plan, while monitoring soil properties, such as pH, nutrients, salinity, electrical conductivity helps to understand soil characteristics and health to optimize fertilization management. The use of fertilizers and pesticides is necessary for the growth and protection of crops. However, excessive and inappropriate use has negative repercussions on the environment, soil and crop health, water resources, and, consequently, on human health. Indeed, when in excess, unused nutrients are retained in the soil and contaminate soil and water through leaching and runoff [79]. Conversely, their deficiency negatively affects crop growth and productivity. Therefore, it is important to emphasize the significance of automated and accurate monitoring systems that take into account the spatial and temporal variability of nutrient concentrations. These systems are essential for avoiding unnecessary and inefficient applications, promoting an optimal and localized application of nutrients, and thereby contributing to the reduction in agronomic and economic losses [79].

Nitrogen is the principal nutrient for plant growth, it is primarily found in the soil, where its concentration depends on the soil type, microbiological and physico-chemical interactions, environmental conditions, and, during the growing season, mineralization, immobilization, and uptake [5]. Plants cannot utilize atmospheric nitrogen directly, so adding chemical nitrogen makes it available and usable for plants; however, overdosing decreases the chlorophyll content, and the plant dries out [78]. Phosphorus and potassium deficiencies also affect plant development and yield. Their deficiency or excessive concentrations cause significant yield losses and toxicity problems in plants [31]. Analytical determinations, while being highly accurate traditional techniques, have significant limitations in terms of cost, analysis time, and sample destruction. To overcome these limitations, the scientific community is focusing on the development of smart agricultural practices. Real-time monitoring through the use of sensors and precision agriculture technologies allows for the collection of valuable data on nutrient concentrations without compromising the integrity of the sample.

The authors [80] propose a high-precision automated system for monitoring soil nutrients, consisting of a pH sensor, a soil moisture sensor, and a fiber-optic NPK sensor. The data collected by the sensors are transmitted to an Arduino UNO microcontroller and sent to a web server via a GSM module. The system compares the acquired data against a reference dataset and sends real-time notifications to the farmer. Through a specific predictive algorithm, the system was able to accurately determine the type and quantity of fertilizer to be used, ensuring an accuracy of 90% [80]. With the IoT configuration, the data are transmitted to the cloud and compared against the threshold values for each measured parameter. This allows for a comprehensive soil analysis, with data easily viewable on the website, enabling the selection of the best crop based on the detected soil characteristics and facilitating timely and informed intervention when necessary. Sensors for monitoring soil nutrients are based on various sensing techniques, ranging from spectroscopic and electrochemical systems to electromagnetic methods. Each approach will be discussed individually, focusing on the positive aspects and potential gaps to be filled. This aims to assess the effectiveness of various technologies and identify aspects for improvement to optimize soil nutrient monitoring

### *3.1. Electrical and Electromagnetic Sensors*

Electrical and electromagnetic sensors operate based on the determination of the apparent electrical conductivity (ECa) of the soil [17] by measuring the soil's ability to accumulate or conduct an electrical charge. These sensors can be categorized into two types based on their need to make contact with the soil and their configuration (Figures 5 and 6). Systems that measure electrical conductivity consist of a transmitter that induces a magnetic field in the soil and a receiver that measures conductivity. These sensors do not require direct contact with the soil and operate at relatively low frequencies [79] to generate an electric current. As a result, the magnitude of conductivity is determined by the generated magnetic field [79], enabling non-invasive and continuous measurements. Electrical resistivity measurement sensors require direct contact with the soil and consist of two electrodes. One is used to generate an electric current in the soil, while the other measures the potential difference, which represents the soil's resistivity [79]. Both types of sensors allow for continuous and non-invasive measurements, providing accurate monitoring of the soil's electrical properties.

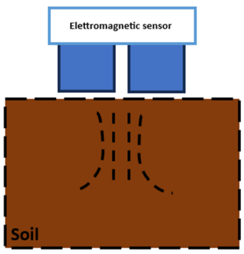


**Figure 5.** Electromagnetic sensor, composed of a generator that creates an electromagnetic field in the soil and a detector that detects the induced variations to determine the soil's electrical conductivity.

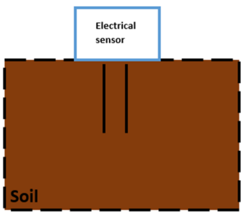


**Figure 6.** Electrical sensor, composed of two electrodes, one of which generates an electric current in the soil, while the other acts as a receiving electrode, detecting the variation in electric potential. This measurement allows for determining the soil's electrical resistance, which is closely related to its electrical conductivity.

Additionally, by varying the magnetic field strength in the first case and the distance between the electrodes in the second, it is possible to determine the apparent electrical conductivity (ECa) at different soil depths [12,79]. Changes in the soil's chemical and physical makeup affect how well it conducts electricity and, consequently, the EC detected by the sensor [81]. The type and amount of fertilizer, texture, soil moisture, irrigation system, and pH significantly influence soil EC, and thus the response of the EC sensor; so, when applying EC sensors to monitor nutrient levels, several factors must be considered [82]. METER Group, USA, offers a next-generation CE probe. The Teros 12 sensor measures soil moisture, temperature, and electrical conductivity. It is small and compact, easy to install, and inexpensive and has a maximum measuring volume of about 1 liter. Gives accurate measurements as it works with low frequency (70 MHz), minimizing the effects of salinity and soil structure [83]. The authors [82] indicate the suitability of the Teros 12 sensor in monitoring soil nutrients. In particular, the addition of inorganic fertilizers was observed to increase the soil EC response, showing a strong positive correlation with soluble nutrients [82]. Nitrogen, in particular, had a significant impact on the sensor's response, suggesting that the Teros 12 is an effective commercial tool for monitoring soil nutrients and supporting crop development. However, its high cost (USD 300–500) makes it less accessible for many farmers. The study [81] demonstrates the suitability of these instruments for monitoring soil nutrients, highlighting the correlation between the apparent electrical conductivity (ECa) of the sensor and the nutrients, with excellent confirmation for nitrogen. However, while the sensor is useful for identifying the presence of nutrients, it does not provide precise determinations of their concentrations, thus limiting its practical application. The authors [84] propose an effective method for performing ion-selective measurements. The study was conducted on a soil paste enriched with known concentrations of electrolytes. By utilizing frequencies ranging from 20 to 250 kHz, an accurate identification of cations was achieved. In particular, these frequencies proved useful for the determination of K + ($R^2 > 0.85$) and $Ca^2$ + ($R^2 > 0.86$) [84]. Electric and electromagnetic sensors provide non-invasive soil monitoring, particularly those systems that measure conductivity, which do not require direct contact with the soil. This minimizes alterations to both the soil and the instrument used. Their versatility allows them to be used in different soil types, facilitating the determination of ECa at various depths. However, these sensors are complex and have a high sensitivity to electromagnetic interference and soil salinity, which can compromise the reliability of measurements. Furthermore, the high costs associated with these sensors make their implementation in low-cost IoT systems difficult. These aspects are summarized in Table 7. The implementation of this technology in low-cost monitoring systems is still limited, but given their importance in performance, it is desirable to integrate them into economical solutions and improve their effectiveness. The market offers various components at affordable prices, starting from just a few dollars, up to more expensive sensors with prices exceeding USD 100. For example, the Teros 12 sensor costs between USD 300 and USD 400. Greater accessibility to these technologies would support more sustainable soil monitoring, promoting more responsible and productive agricultural practices.

**Table 7.** The table compares various types of sensors for soil monitoring, including non-contact sensors, contact sensors, and the TEROS12 sensor. It details the key characteristics of each type.

| Sensor Type | Characteristics | Strengths | Weaknesses |
|---|---|---|---|
| Non-contact soil sensor | They measure electrical conductivity through the magnetic field generated in the soil. These systems consist of a generator and a detector. | - Low frequencies.<br>- Not invasive. | - Not ion-selective.<br>- Sensor reading influenced by soil structure and moisture. |
| Contact soil sensor | It measures the electrical resistivity of the soil. The system consists of two electrodes. | - Low frequencies.<br>- Not invasive. | - Not ion-selective.<br>- Sensor reading influenced by soil structure and moisture. |
| TEROS12 | The sensor measures soil moisture, temperature, and electrical conductivity. | - Non-invasive measurements.<br>- Continuous monitoring.<br>- Versatility in use for various soil types.<br>- Accuracy in measuring moisture and temperature.<br>- Accuracy in measuring nutrients, with excellent confirmation for nitrogen. | - High cost (USD 300–500).<br>- Sensitivity to external interference.<br>- Does not provide precise measurements of nutrients like NPK. |

### 3.2. Electrochemical Sensors

Electrochemical sensors use electrodes to detect and quantify nutrients in the soil. These sensors include ion-selective electrochemical sensors (ISEs) and ion-sensitive field-effect transistors (ISFETs) [79], both capable of selectively detecting specific ions. The sensors are equipped with a selective element to recognize the ion to be detected, such as using a selective membrane, and a reference electrode to measure the electrical potential difference between the soil and the reference solution expressed in mV [79]. ISEs are commonly used because of their excellent performance and ability to measure soil quality directly. They can be placed in direct contact with the soil, allowing for fast and accurate measurements. These sensors can operate either in direct contact with a wet soil sample or in soil solution.

The miniaturized electrochemical sensor developed by the authors [85] represents an important advancement in the monitoring of nitrates in the soil. Its design for direct contact with the ground allows for more precise and timely measurements. The use of a nanocomposite of molybdenum disulfide (POT–MoS2) and poly(3-octyl-thiophene) is an innovation that leverages the unique properties of these materials, enhancing the sensor's sensitivity due to their excellent electrical characteristics and stability. The working electrode uses a patterned gold electrode coated with a selective membrane for nitrates. This method enhances selectivity towards nitrates and ensures specific and reliable results while reducing the risk of interference from other ions in the soil. Calibrating the sensor with standard solutions and extracted soil solutions ensures its versatility and reliability. The results show the ability to detect nitrates in a range of 1–1500 ppm $NO_3^-$ [85], highlighting the sensor's importance for agricultural applications. The authors [86] analyzed the performance of various membranes for measuring soil nutrients using a real-time ISFET sensor. The study revealed that the response of nitrate membranes, using tetradodecylammonium nitrate (TDDA) or methyltridodecylammonium chloride (MTDA), and valinomycin-based potassium membranes is influenced by both the type of membrane and the nature of the soil extractor. The nitrate membrane based on TDDA has shown remarkable ability to detect low concentrations of nitrate in the soil, reaching up to approximately $10^{-5}$ mol/L $NO_3^-$ [86]. On the other hand, the valinomycin-based membranes have demonstrated satisfactory selectivity performance in measuring potassium, even in the presence of interfering cations. These results emphasize the importance of optimizing the membranes to develop more sensitive and reliable sensors. These sensors should be capable of operating effectively even in complex environments where the presence of other ions can strongly influence and cause interference in measurements. An ISE sensor has been developed in [87] for the determination of nitrate in soil, utilizing electrochemical impedance spectroscopy (EIS). This device allows for direct and continuous real-time measurements, eliminating the need for soil pretreatment, and has demonstrated excellent reliability, particularly within the nitrate range of 5 to 512 ppm. During a continuous monitoring period of 7 days, the sensor conducted hourly measurements and required a stabilization time ranging from 12 to 24 h. The results confirmed the sensor's stability and reliability, highlighting an error rate of less than 5% and a coefficient of variation below 20% in long-term nitrate concentration measurements [87]. An IoT device was developed in [88] for the quantification of nutrients in soil. The system comprises an ISFET pH sensor, a soil moisture sensor, and an RGB color sensor, all integrated into the Arduino MEGA 2560 microcontroller board, which is responsible for data acquisition and processing. The integration of machine learning algorithms has made it possible to measure macronutrient levels in the soil with a high degree of precision. In particular the predictive models achieved high accuracies: 95.83% for nitrogen, 98.10% for phosphorus, and 93.75% for potassium [88]. Electrochemical sensors are sophisticated devices that monitor the chemical composition of soil by detecting specific nutrients such as nitrates, potassium, and phosphorus. These sensors are crucial for optimizing agricultural management due to their high sensitivity and fast response times. However, the high costs of the electrodes, which range from USD 300 to over USD 1000 [89], can pose a barrier to broader adoption. Though accurate and portable, further studies are required to improve their accuracy, durability, and selectivity. Their main limitations include high costs, susceptibility to environmental factors, and the need for a good understanding of soil conditions, as well as careful selection of the membrane to avoid inaccurate readings. The strengths and weaknesses of electrochemical methods are summarized in Table 8, highlighting the positive aspects and areas that require further development.

**Table 8.** The table provides an overview of electrochemical sensors used for the detection and quantification of nutrients in the soil. It outlines the main characteristics of these sensors, along with their strengths and weaknesses.

| Sensor Type | Characteristics | Strengths | Weaknesses |
|---|---|---|---|
| Electrochemical sensors | The sensors utilize electrodes to selectively detect and quantify nutrients in the soil. They require a selective element and a reference electrode. The most common types are ion-selective electrodes (ISEs) and ion-sensitive field-effect transistors (ISFETs). Additionally, they can operate in direct contact with the soil or in solution. | - Ion selective.<br>- Measurement of pH and NKP.<br>- High sensitivity.<br>- Rapid measures.<br>- Real time. | - High cost (USD 300–1000).<br>- Minimal sample preparation required.<br>- Requesting specific membranes for each nutrient. |

### *3.3. Optical Sensor*

Multiple and diverse technologies are employed in the implementation of optical sensors. Reflectance spectroscopy is used in optical sensing to determine how much energy is absorbed or reflected. The main spectroscopic methods used in soil monitoring are based on ultraviolet (UV), visible (VIS), and infrared (IR), enabling rapid and non-destructive measurements [90]. NIR systems are based on the theory of harmonic oscillations, which analyzes the molecular vibrations of the bonds between atoms [90]. When the soil is irradiated with frequencies similar to the vibration frequencies of the bonds, part of the radiation is absorbed while the rest is reflected (see Figure 7). The reflectometer measures the reflectance, generating a spectrum that shows the energy absorbed as a function of the radiation wavelength. This spectrum enables the rapid identification of molecules, as each molecule has a characteristic absorption peak. Research [91] has identified specific wavelengths capable of detecting potassium (K) and phosphorus (P) content with good sensitivity. In particular, the 420–480 nm band has proven sensitive to K content, while the 620–660 nm band has shown notable sensitivity to P content. The authors [92] confirm the reliability of these wavelengths and describe an optical NPK sensor that uses an LED as a transmission system and two photodiodes to measure nutrient intensity in the soil. This system has been able to detect NPK nutrients at the respective wavelengths of interest: 950 nm, 660 nm, and 470 nm. These results highlight the importance of Vis–NIR spectroscopy as an effective tool for monitoring soil nutrients.

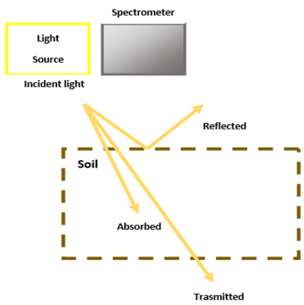


**Figure 7.** Simplified diagram of the operating principle of a VIS–NIR spectrophotometric system: incident light strikes the sample, and the sensor detects the reflected or transmitted light, analyzing the intensity at different wavelengths to determine the soil composition.

Raman spectroscopy measures the change in wavelengths and interaction of scattered light after interacting with a soil sample. Specifically, photons are re-emitted at different frequencies, known as the Raman effect [90]. This process generates a frequency spectrum that provides detailed information about the chemical structure of the molecule, aiding in its identification. The authors [93] analyzed the effectiveness of Raman spectroscopy for determining phosphorus in soils, operating at a wavelength of 785 nm. This wavelength proved particularly advantageous as it allows for enhanced sensitivity in the detection of phosphate compounds. The study conducted by other authors [94] confirms the effectiveness of Raman spectroscopy for phosphorus analysis in soils. The relationship between phosphorus concentration in sandy soil and the corresponding Raman spectra was examined. The calibration results demonstrated excellent accuracy, highlighting the potential of Raman spectroscopy as a promising method for phosphorus detection.

Attenuated Total Reflectance (ATR) spectroscopy operates similarly to infrared techniques, but with some key differences. Instead of directly illuminating the samples, it utilizes a crystal that receives the incident energy [95]. This crystal, placed in direct contact with the sample, creates an evanescent field between them due to the reflection of the energy [95]. The energy then propagates from the crystal to a spectrometer, where a specific spectrum for the analyzed sample is generated. ATR spectroscopy allows for an accurate determination of various soil properties, including nitrogen content, moisture, and organic content [90]. However, direct determination using ATR spectroscopy requires minimal sample preparation but can be affected by potential interferences from water and soil constituents. Additionally, it is crucial to carefully select the type of crystal to be used, as this choice can influence the sensitivity and accuracy of the measurements. The characteristics of optical sensors are summarized in Table 9. A nutrient detection system for soil is proposed [96], utilizing an optical sensor designed for monitoring macronutrients in an IoT context. The data recorded by the sensor re processed by an Arduino UNO board, which allows the conversion of the information into the corresponding values of macronutrients through a dedicated program. The obtained values are transmitted to the cloud via a pair of LoRa units interfaced with ESP8266. The system has demonstrated an error rate of between 1% and 2%, thereby highlighting its accuracy in determining soil macronutrients such as nitrogen (N), potassium (K), phosphorus (P), and soil pH.

Several sensor technologies used in soil nutrient monitoring have been examined, with a particular focus on electrical, electrochemical, and optical sensors. Electrical and electromagnetic sensors, such as the Teros 12, provide non-invasive, continuous measurements of the soil's apparent electrical conductivity (ECa), making them suitable for various agricultural applications. Electrochemical sensors, including ion-selective electrodes (ISEs) and ion-sensitive field-effect transistors (ISFETs), offer rapid and precise nutrient detection capabilities, although their cost may limit accessibility. Optical sensors, which utilize techniques such as Vis–NIR and Raman spectroscopy, enable quick, non-destructive assessments of soil properties and nutrient concentrations. Each type of sensor has specific advantages and limitations. For example, electrical sensors are effective for ECa and nutrient monitoring but are sensitive to electromagnetic interference. Electrochemical sensors excel in nutrient specificity, but they are often costly and can be influenced by environmental factors. Optical sensors provide high accuracy and non-destructive analysis, yet they may require sophisticated calibration and can be sensitive to soil conditions. Overall, although these sensor technologies have proven useful for agricultural management, their integration into low-cost IoT systems requires further development. Future efforts should focus on improving affordability and reliability to enable broader adoption. This approach would promote sustainable agricultural practices and optimize resource management, encouraging more efficient and responsible agriculture.

**Table 9.** The table presents a comparison of different types of sensors used for soil analysis, highlighting their characteristics, strengths, and weaknesses. It includes NIR systems, Raman spectroscopy, and ATR spectroscopy, each with specific methodologies and applications in measuring soil composition.

| Sensor Type | Characteristics | Strengths | Weaknesses |
|---|---|---|---|
| NIR systems | They use the reflectance of light in the visible and infrared bands to analyze soil composition. Typically operate in the 400 nm to 2500 nm. | - Detailed information on nutrient availability.<br>- Fast and non-destructive measurement.<br>- Minimal sample preparation required.<br>- Good sensitivity for detection of specific nutrients. | - Possible interference from moisture and other soil components. |
| Raman spectroscopy | It is based on the inelastic scattering of light, mainly by a laser, which causes changes in the frequency of photons. It operates in the near infrared (NIR) and infrared (IR) range but can also cover the visible. | - Non-destructive.<br>- Provides detailed information on molecular structure.<br>- Can be used for in situ analysis with portable devices. | - Strong dependence on excitation wavelength.<br>- It can be affected by optical interference. |
| ATR spectroscopy | It uses an ATR crystal that receives incident infrared energy, creating an evanescent field that penetrates the sample in direct contact. It typically operates in the medium to long infrared (IR) range. | - High accuracy in measurements, provided appropriate calibration techniques are adopted.<br>- Requires minimal sample preparation.<br>- Non-destructive analysis.<br>- Possibility of rapid and direct analysis. | - Sensitivity to interference from water and soil components.<br>- The crystal must be chosen carefully to optimise sensitivity. |

## 4. IoT Systems for Soil Monitoring

IoT (Internet of Things) systems represent a network of interconnected physical devices that collect, share, and analyze data via an Internet network [95]. These systems, equipped with sensors and software, operate autonomously without the need for human intervention, ensuring real-time monitoring and efficient information management. IoT systems follow a general architecture composed of various interconnected layers, each playing a fundamental role in ensuring the entire process of data collection, processing, and action automation. This structure is outlined in Figure 8 and includes elements ranging from physical sensors to digital services and automation tools, which together enable the development of advanced applications. The physical layer is responsible for the data collection phase. It consists of sensors used to detect specific data, such as temperature, soil moisture, and NPK concentration. Each sensor node is equipped with a microcontroller, such as the ESP8266 and ESP32, by Espressif Systems (Shanghai, China), and Arduino UNO, Arduino Mega manufacted by Arduino (Monza, Italy), to which sensors and actuators are connected via digital interfaces and includes wireless or wired transceivers for communication between individual nodes. The actuators include transducers and electronic circuits that are activated in response to commands sent by the microcontroller [97]. Each sensor and device in the system are equipped with an identification code, such as digital codes or labels, which facilitate recognition and communication with the cloud, enabling real-time data visualization and sharing [95]. Furthermore, IoT systems require a power source connection, such as a battery, USB, or direct electrical grid connection, and may also be supported by a photovoltaic panel.

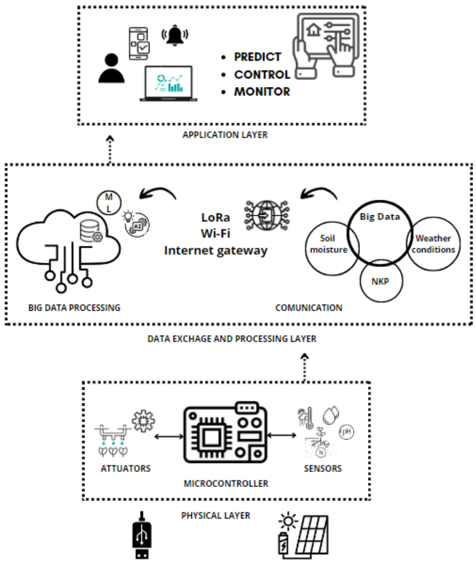


**Figure 8.** Schematic diagram of the IoT monitoring sensor system.

Data transfer occurs via an Internet connection, which enables the collection and transmission of data from sensors and the sending of commands to actuators. Depending on the type of network used, data exchange can occur in two ways: through direct communication, where sensors and actuators have an integrated Internet module that connects them directly to the cloud, or through an Internet gateway system that links the individual components of the physical layer to the network [97]. The first configuration is preferred in contexts where energy conservation is essential, such as battery-powered IoT systems. Conversely, a direct network may be more advantageous in situations where rapid and immediate communication is required. In the cloud, big data are stored, analyzd, and processed, representing one of the most critical phases of the IoT system. Using advanced algorithms, machine learning (ML), and artificial intelligence (AI), raw data are transformed into useful, understandable, and easily accessible information for farmers. This process enables them to make informed decisions based on accurate data. The characteristics of an optimal data processing layer are described in [98] and include the following: interoperability: to facilitate collaboration and information exchange between heterogeneous nodes; scalability management: the layer should automatically apply necessary adjustments when the system undergoes changes; data protection and privacy: ensuring data protection through encryption and safeguarding privacy. The application layer is responsible for the interaction between the system and the end user. It offers digital services for managing and utilizing the acquired and processed information. It relies on a user interface, which can be a mobile app or a website, through which operators can easily view real-time data, send commands, and access historical details. This layer manages notifications and alerts, informing the user in case of detected anomalies. However, a simple and intuitive user interface is essential to enhance the usability and effectiveness of the IoT system. One of the key aspects of IoT systems concerns the choice of communication technologies. These must ensure high-speed, reliable, and efficient data transmission. Additionally, since the process involves significant energy consumption, the chosen technologies should also enable low-power communication, such as that facilitated through Internet gateways. Wireless networking represents a communication technology that uses radio waves to facilitate data exchange between devices. Wi-Fi offers high transmission speeds and supports the rapid transfer of large amounts of data. Although it was not specifically designed to optimize energy consumption or cover long distances, it is still widely used in IoT application. The applicability and reliability of Wi-Fi in IoT systems for the agricultural sector have been demonstrated through numerous implementations of low-cost IoT solutions [13–16]. Thanks to its ability to transmit large amounts of data quickly, this technology proves useful for monitoring and optimizing agricultural operations. However, Wi-Fi is not particularly suited for applications that require wide coverage or low-energy devices, as its limited range and relatively high energy consumption can pose challenges in rural contexts or expansive areas. Wireless sensor networks (WSNs) consist of a series of distributed nodes that collect and transmit data related to various environmental parameters, such as temperature, humidity, and pressure, to a central node. Each node is equipped with a wireless module, enabling direct communication between the sensors and a gateway, which acts as the central node for data management and processing [98]. This architecture allows for the continuous, real-time monitoring of the environment, enhancing operational efficiency and facilitating the collection of critical information for informed decision-making. In [18], the authors developed an autonomous fertirrigation system that utilizes the WSN protocol for communication. This communication technology is characterized by low costs and reduced energy consumption, thanks to its decentralized architecture. WSN, therefore, proves suitable for implementing low-cost IoT systems, especially for large-scale monitoring, as demonstrated in the study [18]. Furthermore, it is particularly well suited for use in remote rural areas, making it an effective solution even in contexts where access to energy resources is limited [28]. Long Range (LoRa) is a wireless communication technology designed for long-distance data transmission [26]. LoRa uses spread spectrum modulation (Frequency Modulation, FM) to transmit audio or data signals via radio waves. This technique enables LoRa to facilitate long-range communication, covering distances of up to approximately 8–15 km, depending on environmental conditions, as highlighted by [25,26]. In studies [25–27], the authors developed IoT systems for soil moisture monitoring using LoRa communication technology. The research demonstrates that it is possible to effectively and cost-efficiently monitor soil temperature and moisture levels by leveraging LoRa. This technology proves to be a powerful and versatile solution for IoT applications, thanks to its ability to enable long-distance communication with low energy consumption. Additionally, LoRa's flexibility and scalability make it particularly suitable for large-scale applications, facilitating the coverage of extensive areas without the need for complex infrastructure. Table 10 summarizes the characteristics of the described IoT systems, which utilize various communication technologies. Additionally, communication can also occur via Bluetooth for devices without a Wi-Fi module. However, the primary limitation of this technology is its reduced range, covering only a few meters [98]. This characteristic limits Bluetooth's suitability for monitoring large areas, such as an agricultural field, where it is essential to maintain a stable and continuous connection over longer distances.

**Table 10.** Overview of the features of the different analyzed low-cost IoT systems, highlighting the main components, monitoring functionalities, and user interface functionalities.

| Ref. | Proposed System | Components | Control System | User Interface | Internet Connection | Activation Conditions | Power Supply |
|---|---|---|---|---|---|---|---|
| [13] | Irrigation system | Micro controller: Arduino UNO by Arduino (Monza, Italy)<br>Sensors: Soil moisture sensor, temperature sensors: LM35 by Texas Instruments (Dallas, Texas), pH, and air humidity sensors.<br>Attuators: Water pump controlled via relay. | Arduino Uno programs irrigation based on soil moisture, activating the pump if necessary. | 16 × 2 LCD display for data visualization. Data sent and displayed on ThingSpeak, with updates every 5 min. Notification system not specified; access to data via online dashboard. | Wi-Fi module. | Irrigation is activated based on the detected moisture levels and temperature, starting the pump if the soil is too dry. | Power supply with a 12 V transformer and relay circuit; board powered via DC jack, USB connector, or VIN pin. |

**Table 10.** *Cont.*

| Ref. | Proposed System | Components | Control System | User Interface | Internet Connection | Activation Conditions | Power Supply |
|---|---|---|---|---|---|---|---|
| [14] | Irrigation system | Micro controller: ESP32 by Espressif (Shanghai, China). Sensors: Soil moisture sensor SEN0308 by DFRobot (Shanghai, China), temperature sensors DS18320 by DFRobot (Shanghai, China), pH, and air humidity sensors DHT22 by AZ Delivery (Deggendorf, Germany). Water flow sensor: Mod FS300 by SEA (Guangdong, China). Attuators: Solenoid valve controlled via relay for irrigation: Hunter PGV-100G by Hunter (San Marcos, USA). | ESP32 controls automatic irrigation based on soil moisture and temperature, activating the solenoid valve during ideal time windows; Blynk allows for manual management and remote monitoring. | Blynk app for remote control and monitoring. Real-time data updates on Blynk, logging the date and time of irrigation, soil temperature, and water flow. | Wi-Fi connectivity. | If the soil moisture is low and the temperature is adequate, and the ESP32 controls automatic irrigation within a specific time; the user can intervene manually. | Powered via battery, micro-USB connection for ESP32. |
| [16] | Irrigation system | Micro controller: ESP32 by Espressif (Shanghai, China). Sensors: Soil moisture sensor YL-69by Jiexing (Guangdong, China) and temperature and humidity sensor DHT11 by AZ Delivery (Deggendorf, Germany). Attuators: Water pump controlled via relay for irrigation. | ESP32 automatically activates the pump if the soil moisture is below the threshold; the Blynk app allows for manual control of the pump and the receipt of notifications. | Blynk app for monitoring and remote control. Irrigation data updated on Blynk with continuous logging; includes date and time of irrigation, soil temperature, and humidity. Email notifications or via the Blynk app. | Wi-Fi connectivity. | Irrigation is automatically activated if the soil moisture drops below the threshold; the pump remains off if the threshold is not exceeded; manual control is available via Blynk. | Direct power via laptop through a micro-USB cable for ESP32. |
| [18] | Automated fertigation system that processes the water requirements of crops. | Weather sensor. Soil sensor (moisture, T, pH/EC). Plent sensor (leaf wetners sensor). Crop database. | Ability to make intelligent irrigation decisions for crops based on ETc. | Data transmission and display on a Web Platform. | Wireless sensor network (WSN). | Strategy that takes into account different irrigation schedules and weather conditions. Daily irrigation quantity and estimated fertilization nutrients based on environmental factors, crop specifications, and soil conditions. | Battery, implemented with a photovoltaic panel. |

**Table 10.** *Cont.*

| Ref. | Proposed System | Components | Control System | User Interface | Internet Connection | Activation Conditions | Power Supply |
|---|---|---|---|---|---|---|---|
| [26] | Air temperature and soil moisture monitoring systems | Micro controller: ESP32 by Espressif (Shanghai, China). Sensors: Soil moisture sensor FC-28 by and temperature and humidity sensor DHT11 by AZ Delivery (Deggendorf, Germany). | Continuous monitoring system of environmental conditions and soil moisture levels. | Cayenne iot Platform for storage and visualization. | The data then transmitted using lora. Data from Source Node will receive by the Sink Node. | The system is designed to continuously monitor environmental conditions and soil moisture, without explicitly specifying whether it is equipped with the functionality to activate irrigation. | Power source not specified. |
| [27] | Soil health monitoring system | Host micro-controller: ATmega 2560 from Atmel (San Jose, USA). Sensors: Soil moisture and temperature Teros12 by Meter Group (Washington, USA). Soil $CO_2$ GMP251, by Vaisala (Vanta, Finland. GPS module for geo-location. Radio module RN2930. Solar panel. | Continuous monitoring of soil health. | IoT-SHM server every 10 min. On the IoT-SHM server, these measurements have been recorded for long-term storage and visualized in real-time using the dashboard. | LoRa communication. | The system is designed to continuously monitor various soil parameters, such as temperature, humidity, electrical conductivity (EC), $CO_2$ levels, and location information. It is configured to send soil measurements to the server every 10 min. However, the system is not integrated with automated irrigation or fertigation systems. | 2500 mAh battery and photovoltaic panel. |
| [28] | Irrigation system | Microcontroller: Arduino NANO from Arduino (Monza, Italia). Sensors: DHT11by AZ Delivery (Deggendorf, Germany). Light-dependent resistor (LDR) for light levels. YL-83 sensor for rainfall levels. YL-69 sensor for soil moisture. Actuator: pump. | Arduino Uno programs irrigation based on soil moisture, activating the pump if necessary. | ThingSpeak, used for the visualization and analysis of collected data. Provides intuitive dashboards for the user, with graphs and reports to monitor field conditions. Allows for the storage of historical data for future analysis. | LoRa communication. | Irrigation is activated when the current time falls within the predefined time windows, and the environmental and soil conditions are favorable for irrigation. | Solar cell and a lithium battery. |

In conclusion, the various IoT communication technologies offer distinct advantages and disadvantages based on key parameters such as distance, energy consumption, and data transmission capacity. LoRa stands out for its ability to cover long distances, making it ideal for large-scale applications, while WSN occupies a middle ground. Wi-Fi, although offering the highest data transmission capacity, is limited to shorter distances and has higher energy consumption. Table 11 provides a comparison between the IoT technologies LoRa, WSN, and Wi-Fi, considering parameters such as coverage range, energy consumption, and operational capacity. Therefore, the choice of the most appropriate technology depends on the specific requirements of the application, such as battery life, range, and the volume of data to be transmitted.

**Table 11.** Comparison between the technologies LoRa, WSN, and Wi-Fi based on distance, energy consumption, and communication capacity.

| Technology | Range | Energy Consumption | Data Transmission Capacity |
|---|---|---|---|
| LoRa | High (8–15 km) | Low | Moderate |
| WSN | Moderate (approx. 10 m per node) | Low | Low |
| Wi-Fi | Shortest (around 100 m) | Higher | Highest |

## 5. Conclusions and Future Prospects

An adequate and efficient management of the soil is essential not only for environmental sustainability but also for increasing productivity, both in terms of quality and maximizing yields. Recognizing potential stressors and critical situations for crops in advance allows for preventive and specific actions to be taken. In this context, the sensors described in the article prove to be promising, offering concrete solutions to address current challenges in agriculture. The adoption of soil monitoring technologies emerges as a key factor in promoting sustainable agricultural practices and optimizing resource use. Soil moisture and nutrient sensors offer significant advantages, enabling more targeted irrigation and fertilization, reducing water consumption, and facilitating a conscious use of fertilizers. The variety of available sensors, including tensiometers, thermal probes, capacitive sensors, TDR, FDR, and neutron moisture sensors, allows for responses to different agricultural needs and conditions. While each of these tools has its advantages and limitations, their integration enables precise and real-time monitoring of soil moisture, greatly improving water efficiency. Additionally, electrical, electrochemical, and optical sensors provide accurate and non-invasive measurements of nutrients. However, the costs associated with these technologies can hinder their widespread adoption. Regarding data transmission, technologies such as Wi-Fi, WSN, and LoRa present various solutions, each suited to specific coverage and energy consumption needs. While Wi-Fi guarantees high transmission speeds, its limited range and high energy consumption make it impractical for rural areas. In contrast, WSN and LoRa are more suitable for large-scale agricultural applications due to their ability to cover vast areas with low energy consumption. The future of soil monitoring and sustainable agriculture appears promising, thanks to continuous technological advancements and the integration of IoT practices. The adoption of cutting-edge systems and the implementation of AI and ML have the potential to radically transform resources management, increasing the efficiency and sustainability of agricultural practices. To fully leverage the potential of these sensors, it is crucial to undertake further research and improvements in various areas, such as sensor calibration, the improvement of connection system, and energy reliability. Developing increasingly accurate predictive models that can improve crop yields, anticipate plant diseases, and optimize the use of fertilizers and pesticides is a critical objective. It is essential to develop AI models specific to different crops, climates, and soil characteristics, making these tools understandable even for farmers without technical expertise. Despite significant progress in data collection, managing that data remains a significant challenge. Future information management systems will need to store, analyze, and show data clearly and accessibly while ensuring ethical protection of information, with particular attention to farmers' privacy. There is also an expected expansion in the use of intelligent systems for the continuous monitoring of soil parameters. These systems should leverage advanced and reliable connectivity technologies, such as 5G and edge computing, ensuring immediate processing and greater precision in corrective actions over large areas.

Such efforts by the scientific community must be accompanied by agricultural policies that adapt to promote the adoption of precision agriculture, encouraging investments in technology and supporting farmers' training. It is fundamental to develop more affordable and durable sensors, improving their reliability and precision through the use of innovative materials and technologies so that they can operate effectively in challenging agricultural environments and be accessible to small enterprises and developing countries. This integrated approach will help make agriculture more sustainable and efficient in the long term, promoting a future in which innovative technologies will benefit all farmers and preserve natural resources.

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