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Soil moisture sensors for sustainable water management in field crop production: A review of advances and application challenges

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SUMMARY

Efficient water management is essential for sustainable production of field crops amid climate change, population growth, and water scarcity. Traditional irrigation practices often lead to water use inefficiency, which harms soil health and reduces yields. To address this, reviewing previous studies on soil moisture sensors provides important context and guidance. Literature from Scopus, Google Scholar, and WoS (2019–2025) on soil moisture sensors for sustainable water management in field crops was screened. Out of 244 retrieved publications, 79 met the inclusion criteria with a focus on sensor technologies, applications, advances, and challenges, analysed thematically for research gaps and insights. Based on the findings, soil moisture sensors boost water management, improve yields of field crops, and support sustainable agriculture. However, hindrances related to high costs, lack of awareness, technical complexity, calibration needs, energy challenges, data interpretation difficulties, and compatibility problems hinder effective soil moisture sensor results. Integrating soil moisture sensors with decision-support tools optimises water use and protects soil health to promote long-term productivity under climate variability. Future research should strategise on the development of low-cost, reliable soil moisture sensors with technology subsidies, training, policy support, durability, integration, and simple data to empower farmers to adopt precision water management.

Keywords: *Soil moisture; irrigation; soil moisture sensors; moisture control; water conservation*

INTRODUCTION

Water is one of the most critical resources in agriculture, and its efficient use is essential due to depletion of freshwater reserves by climate change and population growth (Ingrao et al., 2023). Efficient water management forms the basis of sustainable agriculture in addressing such challenges, particularly in the production of field crops, which are crops cultivated on arable or permanent cropland and harvested in open fields rather than in protected environments, according to Food and Agriculture Organisation (FAO) (2015) definitions (Teweldebrihan & Dinka, 2025). Despite the growing need for sustainable farming practices, water use in field crop production remains inefficient in many regions. As such, soil moisture sensors, which are instruments for systematic measurement of soil water content or potential (FAO, 2024), have emerged as a valuable tool in addressing these increasing challenges, by offering accurate real-time data on soil water content, in a sustainable manner (Zhang et al., 2024). Recent studies reveal that soil moisture sensors help optimise water use alongside other benefits such as enhancing crop productivity and promoting environmental sustainability (Faqir et al., 2024; Zhang et al., 2024; Bagada et al., 2025). Their particular importance is increasingly linked to regions facing water scarcity and where efficient water use is vital for long-term food security. In Central and Eastern Europe, including Hungary, water availability and soil types vary significantly (Mónok et al., 2021; Biró & Kovács, 2024). For instance, Hungarian soils are characteristically heavy clay in the north and sandy in the Great Plain, which influences irrigation requirements and crop water retention (Wadoux et al., 2024). Adoption of precision irrigation technologies such as soil moisture sensors remains relatively low, with recent surveys showing less than 20% of arable farmers using these tools regularly (Kakkavou et al., 2024). These regional characteristics make sensor-based irrigation particularly relevant for improving water efficiency and crop yields under local field conditions. However, despite their potential, the widespread adoption and long-term effectiveness of soil moisture sensors remain underexplored, especially in resource-limited settings and across diverse, climate-risk-prone crop systems.

The management of water in agriculture has become an important concern in recent years, especially with the increasing climatic variability, prolonged droughts, and growing world food demand (Trail & Ward, 2024). The production of field crops, including maize and wheat, requires a significant portion of freshwater use in the whole world (Zhai et al., 2019). Széles et al. (2021) argue that crop functionality is entirely dependent on soil moisture, with negative effects, such as stomatal closure and inhibited root growth, linked to water stress.

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Traditional irrigation practices, based on fixed schedules or visual observations, can be inefficient due to overuse or underuse of water (Sahoo et al., 2022), compared to precision irrigation systems that apply water at variable rates based on site-specific crop and soil needs (FAO, 2021). This traditional approach may encourage wastage of valuable water resources, leading to soil degradation, nutrient leaching, and reduced crop yields (Srivastava et al., 2024). Soil moisture sensors offer a potential solution to such challenges as they facilitate making of informed irrigation decisions. According to Nsoh et al. (2024), these devices are capable of measuring the soil water content and providing real-time data, though their adoption is limited by factors such as technical knowledge, cost, and infrastructure. An evaluation of the technical and practical methods of monitoring soil moisture, as a means of integrating sensor technologies into mainstream agricultural water management, is necessary, as highlighted by Torres-Quezada et al. (2025).

Soil moisture sensors are crucial for optimising the use of water in the production of field crops and promotion of sustainable agriculture, as highlighted by Zhang et al. (2024). Thilakarathne et al. (2025) also explain that through the use of digital probes and wireless connectivity, technology has improved sensor accuracy and combination with precision agriculture tools, which are technologies that manage spatial and temporal variability within fields for efficient input use (FAO, 2022), including Internet of Things (IoTs) platforms and Global Positioning System (GPS)-guided irrigation systems. Research reveals that sensor-based irrigation scheduling can reduce water use by 20–50% without compromising crop yields (Serena et al., 2020; Song et al., 2022; Abdelhamid et al., 2025). Additionally, studies outline sufficient enhancements in water use efficiency coupled with crop productivity and soil health based on moisture scheduling (Hashemi et al., 2024; Lakhiar et al., 2024; Xing & Wang, 2024). Nonetheless, the use of soil moisture sensors in conserving water continues to gain momentum in spite the highlighted challenges such as cost (Parra-López et al., 2025).

This discussion lies in the growing need for efficient water management in agriculture, spearheaded by the rising water scarcity, climate change, and the growing need for sustainable food production. The production of field crops suffers from inefficient irrigation practices that encourage water scarcity, soil degradation, as well as reduced crop yields (Ingrao et al., 2023). In the same way, soil moisture influences the measurements of soil properties like soil organic carbon, which have a direct impact on the production of field crops (Béni et al., 2021). This explains the necessity for use of soil moisture sensors to make precise irrigation decisions suited to crop water needs (Rácz et al., 2021; Zhang et al., 2024). Recent trends of soil moisture sensor technology are described by increased low-cost devices (Zhang et al., 2024), development of open-source sensors for smallholder farmers (Meshram et al., 2024), improved adoption of sensor networks (Hamouda et al., 2024), and increased government support for smart irrigation practices (Rajak et al., 2023). The discussion builds on past findings to assess the practicability of soil moisture sensors in optimising soil moisture for field crops, with a focus on improving productivity while promoting sustainable, resource-efficient farming.

While the merits of soil moisture sensors in optimising water use and promoting sustainable agriculture are well-documented (Faqir et al., 2024; Aarif et al., 2025; Zhang et al., 2025), several critical gaps remain. For instance, much of the existing research focuses on large-scale or technologically advanced farming systems, with limited argument on resource-constrained, low-adoption systems. Also, empirical data linking the use of sensors to long-term improvements in soil health under varying climatic conditions is insufficient. Additionally, there is inadequate analysis on the socio-economic and technical barriers hindering the widespread adoption of soil moisture sensors for field crop production. This discussion seeks to address these gaps by evaluating the practical effectiveness, accessibility, and sustainability impact of soil moisture sensors with the aim of presenting soil moisture management solutions that are more inclusive and adaptable.

MATERIALS AND METHODS

Literature search and selection strategy

Literature was sourced from Scopus, WoS, and Google Scholar databases so as to lower the risk of leaving out important studies, as observed by Ewald et al. (2022). The search took place on 18th August 2025, focusing on documents published within 2019–2025 that has the latest innovations such as Internet of Things (IoTs) integration, Artificial Intelligence (AI)/Machine Learning (ML), low-cost sensors, and Unmanned Aerial Vehicles (UAV)/remote sensing systems. The authors excluded literature older than 2018 to obtain more technologies or methods that would be up-to-date and more practical in modern applications. The search query used was: ("soil moisture sensor*" OR "soil moisture sensor technology" OR "soil moisture sensor systems") AND ("sustainable water management" OR "precision irrigation" OR "water conservation" OR "irrigation scheduling") AND ("field crops" OR "agriculture" OR "crop production"). A total of 244 publications were retrieved from the three databases, Scopus (122), WoS (52), and Google Scholar (70). The documents retrieved were in English and Chinese, and the document types included articles, conference papers, book chapters, and reviews. The publications spanned subject areas, with primary emphasis on Engineering, Computer Sciences, Agricultural and Biological Sciences, Environmental Sciences, and Energy.

Literature processing and analysis

The 244 publications were subjected to screening and inclusion and exclusion criteria, resulting in 79 (28 Scopus, 30 WoS, and 21 Google Scholar) that were

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used in the study. A publication was included or excluded in the study (*Table 1*) if it addressed advances, applications and/or challenges in the context of sustainable water management for field crop production; otherwise, it was excluded. Also, documents written in languages other than English were excluded in order to maintain consistency with the rest of the text. The selected publications were then analysed thematically to identify the patterns and research gaps in sustainable water management practices for field crop production. Additionally, content analysis was conducted to extract qualitative and quantitative insights about soil moisture sensors in relation to sustainable water management in crop fields.

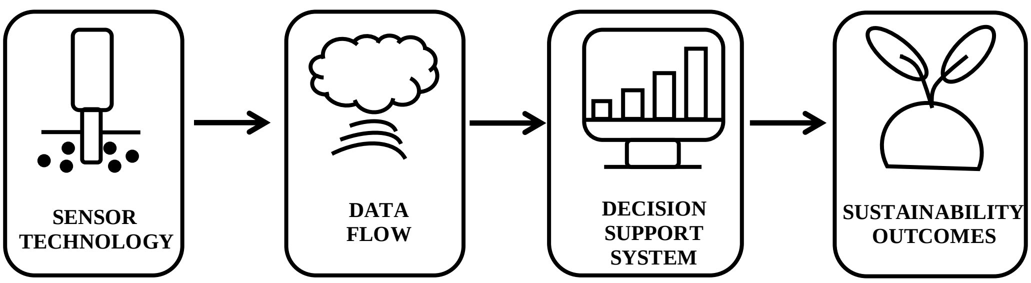
Table 1. **Inclusion and exclusion criteria for literature selection**

Inclusion criterion	Description	Exclusion criterion	Description
Clarity	Focuses on soil moisture sensor technologies, including types, advances, accuracy, calibration, deployment, limitations, or performance.	Not sensor-focused	Mainly about irrigation tools, crop physiology, yield, or water use, without covering soil moisture sensors.
Application	Applies soil moisture sensors to field crop production systems.	Different scale	Focuses on large-scale irrigation planning, aquifer management, or geomorphology rather than field-level soil moisture measurement.
Content evaluation	Discusses the role of soil moisture sensors in sustainable water management, irrigation scheduling, or resource optimisation.	Irrelevant systems	Focuses on hydroponics, vertical farming, containerised plants, or soilless cultures.
		General irrigation automation	About automatic irrigation systems, robotics, drip/sprinkler design, or smart watering without soil moisture sensor focus.
		IoT/AI without soil moisture link	Focuses on IoT, machine learning, cloud systems, or communication networks where soil moisture sensing is secondary or absent.
		Broader sustainability/climate focus	About climate change adaptation, socio-economic adoption barriers, or trends, without direct analysis of soil moisture sensors in irrigation.
		Other sensing technologies	Focuses on nutrient, chemical, or thermo-humidity sensors rather than soil moisture monitoring.
		Non-English	Publication written in languages other than English.

RESULTS AND DISCUSSION

To contextualise the subsequent findings, a conceptual framework was developed to illustrate the interactions between soil moisture sensing technologies, data flow mechanisms, decision-support systems, and sustainability outcomes. This framework guides the interpretation of results discussed in the following sections (*Figure 1*).

Figure 1. **Conceptual framework linking sensor technology, data flow, decision support, and sustainability outcomes**



Source: Authors

Understanding soil moisture sensors: Enhancing water management or irrigation efficiency and sustainability in modern agriculture

Soil moisture sensors are appliances used to measure the volumetric water content in soil during the process of monitoring soil moisture (FAO, 2023). According to Dong et al. (2020), through providing accurate, real-time data to the users, soil moisture sensors can detect the amount of water held by soil at different soil depths. The overall data flow, from field

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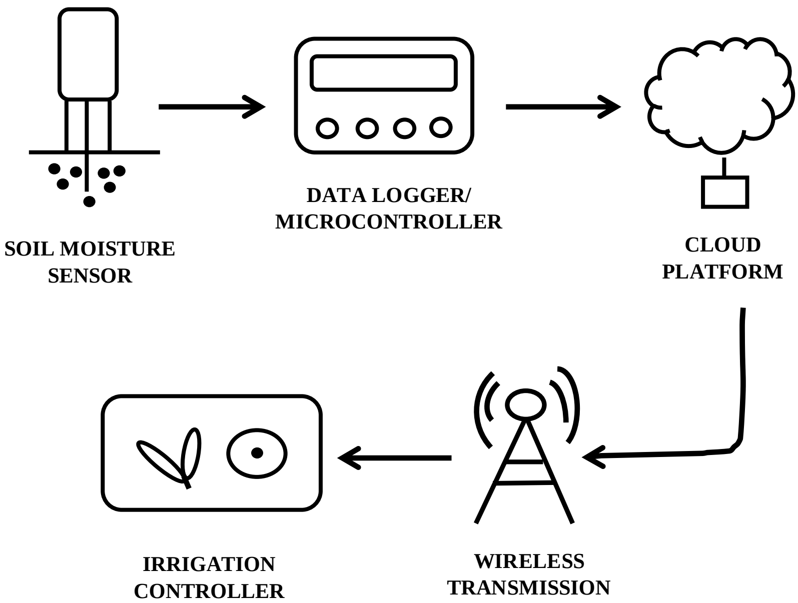
sensing to wireless transmission and irrigation control, is illustrated in *Figure 2*. Depending on their categories; ground, aerial, and satellite (Rasheed et al., 2022), sensors are commonly tensiometers and volumetric sensors. Tensiometers measure the soil water tension (matric potential), that is, how tightly the water is held in the soil and how hard plants have to work to extract it (Menne et al., 2022). Dry soil causes water in the hollow tube to be pulled out of the tensiometer's tube when the device's porous ceramic tip is inserted into the soil, creating a vacuum that the analog or digital pressure sensor measures (Peranić et al., 2022). Volumetric sensors, on the other hand, perform direct measurement of water amount using electromagnetic properties in two ways; capacitance and Time Domain Reflectometry (TDR) or Frequency Domain Reflectometry (FDR) (He et al., 2021). Clearly, according to Hernández et al. (2019), capacitance sensors can estimate the amount of water present in a given soil based on the changes in the dielectric value. TDR or FDR measure availability of soil moisture based on the speed at which the electrical signal travels through a soil, hence the faster the speed the lower the moisture level levels and vice-versa.

Field crops such as maize, wheat, rice, and soybeans are commonly grown over large areas, and they require substantial irrigation, particularly in the drought-stricken regions (Lankford et al., 2023). It is rather difficult to apply water efficiently to such large areas without the right devices. This implies the need for performing site-specific, optimised irrigation, specifically using tools like soil moisture sensors, whereby different spots of a field can be watered on the basis of their unique soil needs (Marković et al., 2024). Soil moisture sensors facilitate creation of a suitable soil moisture balance that contributes to healthier, productive plants and higher-quality harvests (Aarif et al., 2025). This is because sensors help avoid over-irrigation and waterlogging which consequently influence nutrient loss and the build-up of crop root diseases. Additionally, those tools can control under-irrigation and water-related stress which reduce the health and yields of crops (Lakhiar et al., 2024).

Sustainability in agriculture involves meeting current food needs through preserving the environment without compromising the ability of future generations (Hiywotu, 2025). The goal of this sustainability is supported by water conservation, assisted by soil moisture sensors (Zhang et al., 2024). When water, a limited and always an expensive resource, is efficiently utilised, the environment is also protected from runoff and erosion. Furthermore, according to Firoozi & Firoozi (2024), the practice can reduce the impact of droughts when farmers lower their reliance on groundwater, especially in areas with limited access to water or where rainfall is unpredictable. In addition, sensors also encourage a more sustainable use of fertilisers through reduced leaching into waterways (Getahun et al. (2024). These benefits represent a positive return on investment and a user-friendly system for farmers who can utilise smartphones or computers, especially in areas where government subsidies and support programmes are not in effect (Zhang et al., 2024).

Figure 2. **Schematic representation of soil moisture sensing and data transmission process**



Source: Authors

Soil moisture sensing technologies and their applications in agriculture

The increasingly limited resources, such as water, which determine the availability of food for the population, have made the adoption of precision irrigation, a site-specific management practice that optimises water-use efficiency by matching irrigation supply with crop demand, crucial in many developed regions of the world (FAO, 2019; Zhang et al., 2024). The technologies applied in precision agriculture can

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facilitate the optimisation of soil moisture use for the production of field crops and, also, reduce the effects related to the environment. Zhang et al. (2024) argue that an advancement from traditional approaches, such as gravimetric and visual inspection, to the use of soil moisture sensors some of which are mounted on unmanned aerial vehicles (UAVs) provides soil moisture data in a detailed, timely, and economical manner. Worldwide, the focus is on the root zone and topsoil layers as key points for determining soil moisture, as well as the use of soil sensors mounted on moving machinery, especially tractors or seeders, to extract information on moisture levels and other soil parameters like temperature and pH. It is noted that UAVs or drones do not get in direct contact with the soil; however, this challenge is solved by fixing reflectors which connect to TDR or FDR inserted into the soil. Largely, the method has gained popularity through the development of high-precision soil moisture monitoring devices that provide data directly from specific points.

Developments and improvements in soil moisture sensors highlight the value of modern electronic sensors that provide rapid measurements on a broader scale (Bagada et al., 2025). Two categories of sensors are discussed: resistive and dielectric. Resistive sensors are low-cost and require constant calibration, whereas dielectric sensors determine the dielectric constant with high accuracy under varying frequencies using TDR and FDR. The readings of the sensors are set for reliability and accuracy using approaches namely, traditional regression models, Artificial Neural Networks (ANNs) and machine learning algorithms, and calibration. The regression models are used to map sensor outputs and actual moisture levels in the soil, while ANNs simulate the interactions existing between soil properties and the signals recorded by the sensors. Calibration, on the other hand, involves checking the validity of sensor data obtained from fields and comparing it against the results from the laboratory. Bagada et al. (2025) also review the technologies like IoTs integration with the help of platforms that can provide a unified soil moisture monitoring system so as address challenges related to their operation, cost-effectiveness, sustainability, and accessibility.

Optimising the usage of water starts with the efficient soil moisture monitoring. According to Zhang et al. (2025), the strategy involves integrating wireless sensor networks with specific models at specific points of the field. Based on their study, wireless sensors are used to gather moisture data as quick and timely as possible by fixing them within the top 20 centimetres (cm) of the soil profile. The method is improved by calibrating and re-calibrating the sensors, after a specified period of time, to ensure reliability. Additionally, integrating it with models, such as Biswas, can help to estimate the distribution of soil moisture to as deep as 200 cm. Tracking of daily moisture dynamics in a growing crop field qualifies the sensor for a solution against high cost, tool rigidity, water wastage, and water-use inefficiency in agriculture. In a field of a standing crop, manual sampling may be integrated with sensor-based monitoring to measure the volumetric content of soil water. A similar approach described by Zhang et al. (2025) involves vertical installation of sensors (*Figures 3* and *4*) up to about 1 cm for the sensor head to capture moisture dynamics within the crop root zone every after a specified duration. The essence is in the use of remote monitoring systems that apply a wireless, low-cost technology for providing real-time data. Findings indicate a gradual decrease in correlation with the soil depth, which is a critical guide to the prediction of surface soil dynamics as well as water storage in the soil.

Figure 3. **Soil moisture sensors arranged in parallel prior to installation in the field**

Source: Authors (2024)

Figure 4. **Soil moisture sensor installed in an agricultural field**

Source: Authors (2024)

Moisture or humidity is one of the agricultural parameters implemented for the health of soil and plants with the help of sensors (Faqir et al., 2024). As recorded by sensors, soil characteristics, specifically moisture, can facilitate the development of spatial layouts of an area of land. Faqir et al. (2024) argue that the state of the soil may provide useful data that offers a basis for optimum crop yields and correct soil-water relationships for environmental sustainability. There is a significant impact of the amount of soil moisture on the general condition of soil. Depending on their operational systems, soil moisture sensors may exist as

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capacitive-based (for detecting soil moisture on the basis of fluctuating soil dielectric constant in proportion with the level of moisture), electromagnetic induction (EMI)-based (for providing quick data with the help of coils that access deep soil layers), and ultrasonic-based (for categorising the soil moisture content using ultrasonic waves recorded on the detector). There are sensor limitations such as minimal infiltration depth, high cost, and susceptibility to interference. However, as recommended by Faqir et al. (2024), these can be addressed by integrating sensors with IoTs connectivity, innovating wireless technologies, and analysing the output data using artificial intelligence (AI). All in all, monitoring the moisture levels can considerably influence the productivity of soil. The moisture data provided by sensors can inform the conditions for crop growth and final production.

Water is a foundation for farm output despite undergoing the rising threat resulting from a drastic population growth, fluctuating habits for its utilisation, together with the global changes in climate (Kishore et al., 2025). Overall, agriculture leads, with about 70%, the activities that heavily withdraw water from the sources on a world-wide scale. The search for efficient water management has produced a number of methods, although some of them offer little remedy due to their exacerbating inefficiency characterised by more water wastage. Irrigation systems based on sensors can offer support to the traditional irrigation types because they facilitate improved water-use efficiency through instant soil moisture monitoring. Kishore et al. (2025) further explore the different soil moisture sensors such as granular matrix sensors, tensiometers, and neutron moisture probes. Additionally, a study conducted on automating drip irrigation at the Zonal Agricultural Research Station, Bengaluru, India yielded 18.58% out of the 25% available soil moisture depletion, accounting for a percentage total of 74.32% water savings compared to the conventional drip irrigation. These results confirm that sensors aid the reduction of application of water but they improve crop yields, providing a guide to the sustainable management of the water resource especially in soils that are water-stressed.

Water scarcity poses a severe global threat to agricultural systems mainly in in the tropics. According to Torres-Quezada et al. (2025), the threat is worsened by climate change and increased utilisation of fresh water by the population. About 70% of freshwater use in the whole world is susceptible to a water management crisis. Field crops, even under irrigation management, use their fine roots in the topsoil surface zone in response to water uptake from the soil. Specifically, through the use of drip and overhead sprinkler irrigation methods, these surface zones may be subjected to water loss by evaporation. This makes it critical to determine how much water to apply to a crop field and when. Soil moisture sensors are technological devices that can provide both historical and real-time data for monitoring water stress and optimising water use. Field-based soil moisture sensors can be used to accurately and widely detect soil moisture, including its dynamics like evaporation tendencies, between 10 and 60 cm as validation of the satellite remote sensing technologies. Torres-Quezada et al. (2025) report on cases where Normalised Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) are analysed together with soil moisture data to determine crop response to water stress. Their results indicate a high soil moisture variation at 30-cm depth due to the influence of seasonal changes and evaporation, making soil depth a critical factor of optimising water use in field crops. Similarly, Thapa et al. (2019) note soil moisture as a major determinant of crop performance, which requires monitoring of plant health with NDVI so as to ably track how crops are responding to water availability in the soil.

Maximising crop yield is dependent on practices of effective water management, according to Somefun et al. (2024). This approach includes risk management arising from climate change, using optimised water use efficiency. In this case, technologies like soil moisture sensors are employed to schedule the irrigation as part of precision farming, whereby farmers can apply only the right water quantity to a given crop at the right time. The sensors, including neutron probes, TDR, and tensiometers, contribute to less wastage of the water resource and increased sustainability in agriculture and environment. Moisture sensors provide site-specific crop management since they are fixed at various soil depths. Other operational requirements are; how to strategically position the sensor in the root zone, such as close to the drip line and crop row, and how many sensors to install. These are fulfilled on the basis of growth stage of a crop and field variability respectively. Somefun et al. (2024) notes that where there is need for enhancing water use efficiency with reduced labour, soil moisture sensors may be integrated with simulation models in order to estimate moisture use in field crops over time. Even water-related practices like irrigation are initiated at a point when the crop water needs fall below the threshold; nevertheless, the sensors can be used to preserve 40 to 65% water in fields of vegetable crops (like tomatoes) and cereals (like corn).

Agricultural land under irrigation is a situation that imperatively demands for efficient use of water (Raxbaroy, 2024). This is further explained by differences in soil types that offer varying water retention capacities. For instance, according to Raxbaroy (2024), water in sandy soils is drained faster while clay soils are able to retain water for long. Besides, the more moisture a soil retains, the longer it takes for field crops to grow successfully in dry conditions. Improving the efficient use of soil requires regular monitoring of its ability to retain water. Attempts have been made to employ traditional methods for measuring soil moisture; however, such methods are found to be labour-intensive and time-consuming. Raxbaroy (2024) further reports that IoT-based sensors and automated systems provide a reliable solution through accurate and immediate monitoring and optimisation. Relatedly, the technologies enhance

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water conservation, as well as controlling soil degradation and enhancing the productivity of field crops, especially in circumstances where sustainable agriculture is desired amidst water scarcity. Soil moisture levels are recorded based on varying depths and specific time intervals, such as 20 minutes, and then the average is calculated to provide guidance for revising the watering processes. With the help of IoT technologies, moisture levels are measured and monitored at various points and depths in a field, and then data processed after its continuous transmission via Wireless Fidelity (Wi-Fi).

Field crops have been produced over the years under precision agriculture with a transformation from the use of traditional GPS methods to systems operated by AI (Kumar, S.V. et al., 2024). Equally, evolution defines the digitalisation path taken in obtaining efficient and productive outcomes. Mgendi (2024) confirms that precision agriculture is taken to a higher level by using sensor technology together with GPS and wireless devices. Sensor technology enables farmers to determine soil conditions, specifically moisture levels, and make watering decisions for their field crops based on data transmitted to the central database. This innovation facilitates resource optimisation, whereby soil moisture sensors are fixed at strategic points below ground at different layers to capture continuous real-time readings. These readings form the basis of precise water management or water usage by reducing the risk of under- or over-watering. For instance, in the almonds orchards study conducted in California, water usage reduced by 33% without compromising the crop's optimum yields. Despite the higher initial cost, high expertise level, and infrastructure limitations involved, this result could justify the relevance of adopting the use of soil moisture sensors in practical management of water stress (Kumar, V. et al., 2024). However, necessary training, technological collaboration, and government support could help the vulnerable communities cope with the innovation.

Farmers of field crops continue searching for methods that can solve food insecurity without compromising the sustainability of the environment (Helmy et al., 2024). About 33% of the Earth's surface is covered under arid climate, characterised by low precipitation levels and continuous water scarcity that severely impacts the growing of crops. The situation tends to worsen, with explosive population growth and growing demand for water, when the existing water resources are not attended to. One of the initiatives for precision agriculture is water scheduling through smart irrigation strategies to ensure appropriate soil water retention. However, optimising the irrigation schedule requires use of sensors that help in monitoring the soil moisture conditions either temporal or spatial. Helmy et al. (2024) highlight sensors of electromagnetic methodologies such as TDR, capacitance sensors, neutron probes, and tensiometers that are used in measuring soil moisture content. A capacitance sensor tried out at Cairo Experimental Station (Egypt) recorded 19.87% to 41.86% water savings, in sandy clay loam soil, compared to the use of traditional irrigation in the growing of lettuce. Other sensors measure the moisture based on soil resistivity, whereby electrodes are inserted into the soil: when the resistivity is low, the soil will be wetter and vice-versa. The technique is recommended for its being quite straightforward and affordable, despite requiring careful calibration and installation.

Different soil moisture sensors applicable for field crop production

In *Table 2*, an overview of the major soil moisture sensor types is presented, as extracted from the publications and reported contexts. Each sensor technology offers distinct advantages, limitations, and applications depending on the needs, conditions, and strategies for monitoring, soil sustainability, and irrigation priorities. Some traditional devices like tensiometers, and those meant for sub-surface moisture determination like the TDR are referenced, together with the affordable electrodes (Hardie, 2020; Mane et al., 2025).

Table 2. **Frequency of soil moisture references across applications**

No.	Sensor type	Frequency of mentions	Applications / Contexts
1	Capacitive sensors	13	Detect soil moisture via dielectric constant fluctuations.
2	Electromagnetic induction sensors	9	Quick measurement from deep soil layers.
3	Ultrasonic sensors	14	Measure soil moisture using ultrasonic waves.
4	Granular matrix sensors	3	Improve irrigation efficiency.
5	Tensiometers	9	Measure soil tension; used in automated irrigation, precision agriculture, and electromagnetic methodologies.
6	Neutron moisture probes / Neutron sensors	6	Measure soil moisture; used in precision irrigation, automated systems, and simulation models.
7	Time Domain Reflectometry (TDR)	3	Applied in precision agriculture and electromagnetic methods.
8	Capacitance sensor	5	Measures specifics in lettuce irrigation experiments.
9	Electrodes / Resistivity-based sensors	9	Straightforward, affordable method using soil resistivity to measure moisture.

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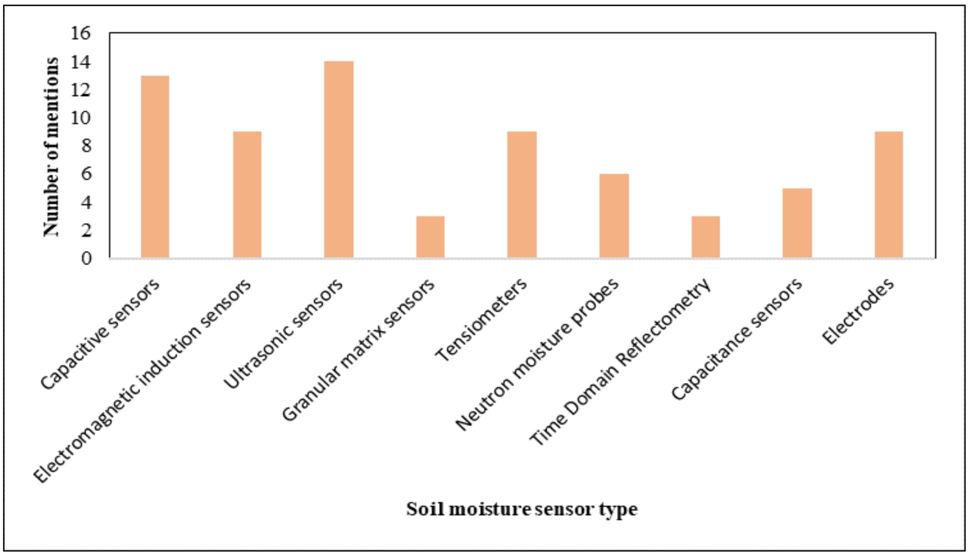
Ultrasonic sensors (14 mentions) and capacitive sensors (13 mentions) were the most frequently cited sensor types, suggesting dominance, more versatility, and wide testing across studies. Thus, the text's observation is aligned with technologically advanced systems, whereby these sensors are sophisticated and suitable for controlled and large-scale setups (López-Villanueva & Rivadeneyra, 2020). Moderate attention was paid to tensiometers (9 mentions), electromagnetic induction sensors (9 mentions), and resistivity-based electrodes (9 mentions) that appeared frequently, showing steady use in precision irrigation and automated systems. However, their adoption may still be constrained by barriers such as costs, infrastructure, and user-training. Granular matrix sensors and TDR had 3 mentions each, representing limited exploration despite their potential in water-saving irrigation (Tornese et al., 2024). This suggests that research remains underdeveloped on low-cost, simpler, and more suitable tools that could be the resource-constrained farmers' choice. Other specialised devices are neutron moisture probes (6 mentions) and capacitance sensors (5 mentions), cited in experiments and modelling such as simulation and lettuce irrigation. These devices may face barriers in broader adoption due to technical complexity, regulation, and safety. The frequency of mentions (*Figure 5*) also suggests that researchers are prioritising high technology devices; however, the limited presence of low-cost, farmer-accessible methods highlights the socio-economic barriers on the part of field crop producers.

Figure 5. **Comparison for the frequency of soil moisture sensor mentions in texts**



Source: Authors

Resource-constrained, low adoption systems of moisture sensors for long-term soil health

Soil moisture sensors have been beneficial in field crop production, making it easy for farmers to enhance irrigation scheduling and conserve water resources. These sensors facilitate precision water supply in the soil thereby promoting healthier plant root development, nutrient uptake, and higher crop yields (Rajak et al., 2023; Faqir et al., 2024). Research on advanced technologies of soil moisture monitoring also indicates that integrating sensors with decision-support devices promotes efficiency, especially under climate variability (Zhang et al., 2024). All these studies highlight how real-time soil moisture monitoring reduces waste, hence promoting productivity and sustainable water management practices through precision irrigation and soil moisture monitoring, consistent with FAO's framework for efficient water use in agriculture (FAO, 2020). This suggests that water levels are kept, soils optimal retain their natural structure, and beneficial microbes are protected. Consequently, farmers can achieve long-term improvements in soil health when such practices are performed repetitively (Lakhiar et al., 2024; Abdelmoneim et al., 2025).

Soil moisture sensors have technologically evolved over the years (Bagada et al., 2025; Mansoor et al., 2025; Zha et al., 2025; Zhang et al., 2025). Concerning the stability of soil moisture sensors, there have been improvements in sensor accuracy, durability, and calibration across diverse soil types. According to Faridah et al. (2025), sensor accuracy reduces with long-term usage hence requiring approaches for more reliable, long-term field applications such as regular cleaning and calibration. Similarly, Yu et al. (2021) and Qi et al. (2024) highlight innovations like calibration that combine moisture and salinity measurements for providing clear indicators of soil health. These studies enable farmers to make informed decisions on irrigation using sensor-based systems and data-driven resource-efficient practices. This increased evidence of sensor technology can expand the scope for sustainable agriculture globally. It implies that the advancements directly protect the health of soil by avoiding

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salinisation and increasing aeration and soil biodiversity. Based on the observation made by Topa et al. (2025), it is necessary to apply data-driven irrigation so as to improve soil structure and organic matter stability and lower the harmful cycles of drought.

Soil moisture sensors play a transformative role in achieving sustainability through real-world applications. Besides the technical aspects, farmers apply soil moisture sensors to improve soil and water (Dhanaraju et al., 2022; Eze et al., 2025). This means that field crop producers adopt the use of sensors to apply reduced amounts of water without compromising yield. Relatedly, Seyar et al. (2024) describe how combining field sensors with satellite data can increase soil water management strategies. This is possible when farmers can allocate water more efficiently, through technical connection of localised soil data to larger monitoring networks, in water-scarce regions. Therefore, sensor-based irrigation is beneficial to sustainable agriculture in terms of water savings, reduced energy use, lower input costs, and long-term resilience of field crop production. Reliably, soil moisture sensors should be adopted and used in integration with remote sensing in order to achieve the integrity and nutrient content of soil. Additionally, this can create more benefits such as reduced runoff, erosion, and long-term fertility (health).

Socio-economic and technical barriers that hinder the widespread adoption of soil moisture sensors

Socio-economic barriers

The adoption of soil moisture sensors is obstructed by high purchase and installation cost. Many small-scale farmers may not afford even the low-cost models due to the developing state of their countries, as observed by Iqbal et al. (2020). On top of sensors, there are noticeable investments required in terms of irrigation controllers, data loggers, and wireless transmitters, all of which are expensive (Puig et al., 2022). Besides, the invisibility of return on investment makes the resource-constrained farmers hesitant to adopt such systems (Abebe et al., 2020). Moreover, farmers find it even harder to justify the purchase of these sensors due to little or no financial incentives from governments and institutions. This makes affordability a focal challenge in areas where field crop production is mainly subsistence-based.

Limited access to financial resources often bars farmers from adopting soil moisture sensors despite the potential benefits attached to these devices (Pandeya et al., 2025). Investment in precision irrigation technologies is further affected by the unavailability or insufficiency of financial programmes like loans (Autio et al., 2021). Even financial institutions may not risk lending farmers such agricultural technology in areas prone to drought or market fluctuations. The lack of such support compels farmers to make personal savings or rely on informal borrowing, both of which limit large-scale adoption of soil moisture sensors and encourage traditional irrigation practices (Khan et al., 2024).

There is a lack of awareness and technical knowledge among field crop producers concerning the working and benefits of soil moisture sensors (Sutanto et al., 2022). In most cases, small-scale farmers apply traditional means of deciding when and how much to irrigate. Thus, farmers rely on visual inspection of crops or intuition, avoiding sensor-based decision-making that they consider excessively complicated. Barriers such as calibration, insufficient training on installation, and data interpretation also prevent the effective use of sensor moisture sensors. The absence of, or little, capacity-building and knowledge dissemination (through extension services) complicates soil moisture sensor adoption and reduces farmers' trust in these technologies (Raji et al., 2024).

Farmers in many areas are accustomed to traditional irrigation methods and may consider the use of soil moisture sensors as a risky investment (Lakhiar et al., 2024). Such cultural attitude is worse in communities where there are no visible examples of successful implementation of these tools. Farmers of field crops often resist the adoption of these tools due to fears associated with technology failure and money wastage (Yue et al., 2023). Some are not sure of how moisture sensors improve crop yields and water use. Furthermore, peers, including neighbours and community leaders, lead to reluctance of farmers to adopt these technologies even in situations when they are affordable (Thilakarathne et al., 2025). Therefore, in cases where cultural perceptions are strong there must be technical training to ensure successful technology diffusion.

Soil moisture sensors are part of precision irrigation strategy whose technology requires support from government and institutions (Lakhiar et al., 2024). In low-income regions, however, farmers usually lack a strong backing for the adoption of these new technologies. Most times, the weak policies in certain regions discourage research and development funding, which reduce the availability of low-cost sensors suitable for region-specific soils or climate (Huang & Wang, 2024). Moreover, the gap between research and field crop producers would be bridged by extension services; however, low funding and ineffectiveness deter the adoption process (Jaiswal et al., 2025). Unclear policy frameworks and incentives encourage initiatives that are dependent of individual farmers, which is insufficient for large-scale transformation in soil moisture sensor use.

Technical barriers

The adoption of soil moisture sensors is hindered by difficulty in maintaining accuracy in various environmental conditions. Parameters such as texture, salinity levels, and organic matter content can determine the reliability of sensor readings, which requires frequent calibration (Adla et al., 2020; Kulmány et al., 2022). For instance, a sensor used for sandy soils may provide inaccurate measurements when used in clay-rich soils, and this may cause over- or under-irrigation. Additionally, changes in temperature and season also interfere with sensor

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performance, which implies constant adjustments, complexity, and high cost (Abdinoor et al., 2025). The results of this technical barrier are loss of farmer confidence and low appeal for sensors as irrigation management tools.

The durability of soil moisture sensors is limited in harsh environments for field crop production (Bagada et al., 2025). Conditions such as fluctuating moisture levels, extreme temperatures and soil chemicals weaken the effectiveness of sensors over time. For example, when corrosion affects the metallic probes, or plastic casings become weak, and microbial growth damage the sensitive components, it influences frequent replacements and repairs (Baylakoğlu et al., 2021). Even maintenance needs such as cleaning, recalibration, and battery replacement are time-consuming and impractical for farmers managing large crop fields (Adla et al., 2024). Therefore, farmers faced by these repeated failures abandon sensors with a perception that the technologies are unreliable.

The practice of combining soil moisture sensors with systems of wireless and IoT-based irrigation comes with energy- and connectivity-related challenges (Balasooriya et al., 2020). Many sensors use batteries or solar-powered appliances that may not work efficiently in environments that are remote or cloudy (Kumar, S.V. et al., 2024). This presents a charging or battery replacement burden for field crop farmers who lack access to reliable electricity. More still, systems that are IoT-based require strong and stable internet connection, which is always unavailable in isolated regions (Siraparapu & Azad, 2024). These energy and connectivity hindrances deny farmers the opportunity to fully utilise advanced monitoring and automation features, which constrains the general effectiveness of water management in field crop production.

Soil moisture sensors work alongside irrigated systems to produce reliable results (Dong et al., 2020; El-Naggar et al., 2020). However, combining these functions are quite complex and they require accessories such as controllers and pumps. Therefore, for farmers of field crops to install and manage such facilities there must be external assistance. In addition, there are compatibility issues between various kinds of sensors and water control equipment, implying that farmers must invest in expensive and technically demanding facilities (Mandal et al., 2024). Furthermore, there should be simplified system designs and complete systems, devices, and applications that work together for improved effectiveness of soil moisture sensors. Unfortunately, this is only limited to experimental projects and large-scale crop farms which are capable of utilising advanced technology.

Interpreting sensor data presents significant complexities, especially where the readings are recorded in units that farmers cannot understand without training (Maraveas et al., 2025). Field crop production practices involving soil moisture sensors may not match with the available decision support systems (Schattman et al., 2023). Consequently, farmers may ignore or misuse sensor data, leading to poor irrigation decisions. Scaling the sensor technologies to large fields often lead to difficulties as farmers try to use of multiple sensors to capture spatial soil moisture variability (Rasheed et al., 2022). Also, this data becomes too large to manage using simple analytical tools that are owned by majority of smallholder farmers. This reduces the practicality of soil moisture sensors among such farmers, hence the low adoption.

CONCLUSIONS

Soil moisture sensors represent a promising innovation for the production of field crops as well as advancing sustainable water management using improved irrigation efficiency, enhanced crop productivity, and conservation of scarce water resources. The integration of sensors with emerging technologies such as IoT, AI, and UAVs, as recorded in various literature, further widens their practical uses especially in areas at the risk of water scarcity. Nevertheless, significant challenges remain pertaining to accessibility, affordability, and adaptability in resource-limited and climate-sensitive conditions. As discussed above, addressing these gaps is essential to ensure inclusive sensor adoption, long-term soil health benefits, and flexibility for sustainable agriculture.

Also, by providing real-time and site-specific data, soil moisture sensors facilitate the optimisation of irrigation scheduling, while conserving scarce water resources and alleviate conditions such as nutrient leaching, crop stress, and over-irrigation of crop fields. More supplements to these sensors that serve as modifiers, such as wireless networks, IoT platforms, and machine learning enhance their effectiveness, which allows better decision-making and preservation of soil health for a long time. Consequently, soil moisture sensors promote sustainable productivity while protecting the field crop growing environment and other natural resources whose goal is to meet future food demands.

Finally, the widespread adoption of soil moisture sensors is constrained by socio-economic and technical barriers, ranging from high costs and maintenance challenges to connectivity issues. Smallholder farmers in regions constrained by resources do not benefit from these technologies due to limited financial support, training, and infrastructure. Addressing these barriers require collaborative action through government subsidies, extension services, technological innovation and farmer-friendly models. Ultimately, sustainable water management in field crop production will depend on bridging the gap between advanced soil moisture sensor technologies and practical adoption at all scales of field crop production.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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