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Sensors for enhanced crop monitoring and management: Technologies, applications and future perspectives

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Abstract

India has a vast agricultural sector, with around 55% of its population involved in farming. Over the years, farming practices have evolved significantly. Precision farming is a modern technique that uses technology to manage crops and soil effectively. It relies on tools like GPS, sensors and drones to analyze specific field conditions. Different types of sensors are essential for precision agriculture. Optical sensors help differentiate between soil and vegetation by using light reflectance. Electrochemical sensors assess soil nutrients, pH and organic matter for better nutrient management. Various crop nutrient sensors, such as ISE/ISFET and SPAD, monitor nutrient levels to enhance fertilizer efficiency and reduce environmental impact. Efficient management of soil and water is vital for sustainable farming practices. Tools like TDR measure soil moisture by sending and reflecting frequencies. Advanced sensors provide high sensitivity in monitoring soil health. IoT, wireless sensor networks (WSNs), and AI transform agriculture through real-time monitoring and predictive analytics. These technologies aid in optimized irrigation, precise nutrient management and early pest detection. To promote widespread adoption and strengthen food security, challenges need to be addressed through farmer training, subsidy and improved infrastructure.

Keywords: Precision agriculture, soil moisture sensors, internet of things, wireless sensor networks, smart farming

1. Introduction

The global economy and food security are still largely dependent on agriculture, especially in developing nations like India where a sizable section of the populace makes their living from farming. The need for sustainable and effective agricultural techniques has increased due to factors such as rapid population development, climate variability, shrinking arable land and growing reliance on natural resources. Conventional farming methods, which Mostly depend on manual observation and consistent input application, are frequently ineffective and do not take into consideration the temporal and spatial diversity within fields. In this regard, precision agriculture has become a revolutionary strategy that incorporates cutting-edge technologies to maximise crop yield while reducing environmental effects (Blackmore, 2000; Gebbers and Adamchuk, 2010).

According to Pierce and Nowak (1999), "Precision agriculture can be defined as the application of principles and technologies to manage spatial and temporal variability associated with all aspects of agricultural production for the purpose of improving crop performance and environmental quality". Precision agriculture is a new approach that uses data-driven management techniques to increase crop output and sustainability. This method focuses on administering inputs like water, fertilizer and pesticides in a site-specific way while keeping an eye on the temporal and spatial variability within agricultural fields. The use of sensors that gather data on soil, crop and ambient variables in real time is crucial to the successful use of precision agriculture. According to Gebbers and Adamchuk (2010), these sensors let researchers and farmers make well-informed management decisions that increase productivity while reducing environmental effects [9, 19].

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Sensor technologies are becoming crucial instruments for keeping an eye on field conditions and crop health. In agriculture, optical and spectral sensors are frequently used to distinguish between soil and plants and assess crop development and stress conditions by measuring reflected light. According to David Mulla (2013), these sensors can detect changes in plant vigour and spot any problems like disease or nutrient deficiencies early on, allowing for prompt management interventions.

Alongside optical sensing technologies, electrochemical sensors are crucial for evaluating the chemical characteristics of soil. Devices like ion-selective electrodes (ISEs) and ion-sensitive field-effect transistors (ISFETs) are capable of measuring essential soil variables such as nutrient levels, pH and organic matter content. These insights enable farmers to adopt precise nutrient management practices, enhance the efficiency of fertilizer usage and minimize environmental pollution resulting from the overuse of agrochemicals (Mishra, 2017).

Tracking the physiological condition of plants is vital for enhancing crop yields. Devices like chlorophyll meters, including SPAD sensors, are frequently utilized to assess the chlorophyll levels in leaves, which are closely linked to the nitrogen status of the plants. These sensors enable quick and non-invasive readings, facilitating better fertilizer management and promoting sustainable agricultural practices (Schlemmer *et al.*, 2005).

Effective management of soil and water is a crucial component of contemporary agriculture, especially in the face of growing water shortages. Soil moisture sensors, such as time-domain reflectometry (TDR) systems, are commonly employed to precisely assess soil water content. These devices send electromagnetic signals through the soil and analyze the reflected response to gauge moisture levels, enabling farmers to plan their irrigation more efficiently and save water resources (Topp *et al.*, 1980).

Recent advancements in digital technology have significantly improved the functionality of sensor-based agricultural systems. By combining sensors with the Internet of Things (IoT), wireless sensor networks (WSNs), and cloud computing, continuous data gathering, remote monitoring and automated management of agricultural activities are possible. These intelligent farming systems facilitate real-time observation of field conditions and aid in decision-making processes that enhance crop management and the efficient use of resources (Jawad *et al.*, 2017).

Artificial intelligence (AI) and machine learning are increasingly utilized in agriculture to process extensive amounts of data generated by sensors. These technologies facilitate predictive analysis, detection of crop stress, estimation of yields and precision management techniques that improve productivity and sustainability in farming. By integrating sensor technology with sophisticated data analysis, contemporary agricultural systems can enhance their efficiency and resilience against environmental challenges (Liakos *et al.*, 2018).

While sensor-based technologies in agriculture offer substantial advantages, their broad implementation encounters various obstacles. Factors such as high upfront costs, a lack of technical expertise among farmers and insufficient rural infrastructure can hinder the adoption of precision agriculture technologies, especially in developing areas. To facilitate the uptake of sensor-based crop monitoring systems and enhance global food security, it is crucial to tackle these issues through initiatives like farmer education programs, supportive government measures and increased access to technology (Food and Agriculture Organization, 2017) [17, 22, 24, 11, 14, 7].

2. Types of sensors

2.1 Soil moisture sensors

Soil moisture plays a crucial role in the growth of plants, the productivity of crops and the sustainability of our agricultural practices. It directly influences how much water is available to plants, how they absorb nutrients, the activity of beneficial soil microbes and various physiological processes in crops. Because of this, managing soil water effectively is vital for optimizing irrigation, boosting crop yields and conserving our precious water resources. In recent years, soil moisture sensors have become essential tools in precision agriculture and modern farming. These sensors allow for continuous monitoring of the water content in the soil, enabling farmers to make data-driven decisions about irrigation (Adamchuk *et al.*, 2004; Gebbers and Adamchuk, 2010). Traditionally, soil moisture measurement involved methods like gravimetric analysis, where soil samples are taken and dried in an oven to determine water content. While this approach is accurate, it's pretty labor-intensive and not suitable for real-time monitoring in the field. This has led to the rise of advanced soil moisture sensors that provide rapid, non-destructive and constant readings, making them perfect for everyday farming needs (Zhang *et al.*, 2002). These sensors work on different principles. For example, resistance-based sensors measure soil moisture by detecting changes in electrical resistance between two electrodes buried in the soil. When the soil gets wetter, its electrical conductivity improves and the resistance drops. These sensors are generally inexpensive and easy to use, but their readings can be influenced by factors like soil salinity and temperature changes (Adamchuk *et al.*, 2004). Capacitance based sensors, on the other hand, estimate moisture levels by measuring the soil's dielectric constant. Because water has a much higher dielectric constant compared to soil particles and air, these sensors can detect changes in water content through fluctuations in capacitance. They're popular in modern agriculture for their quick response times, affordability and compatibility with automated systems (Mcbratney *et al.*, 2005). Many are integrated with data loggers and wireless systems to provide real-time moisture readings. Time Domain Reflectometry (TDR) sensors take a different approach. They assess moisture by looking at how long it takes electromagnetic pulses to travel through a probe inserted into the soil. The speed of these signals depends on the soil's dielectric properties, which relate directly to its water content. TDR sensors are known for their accuracy and reliability, but they tend to be more expensive and often require specialized equipment for data interpretation (Adamchuk *et al.*, 2004). Frequency Domain Reflectometry (FDR) sensors are somewhat similar but measure changes in frequency instead, offering a simpler and more cost-effective alternative. In agricultural practice, soil moisture sensors are crucial for effective irrigation management. Having accurate soil moisture data helps farmers know when and how much water to use, resulting in less waste and more efficient irrigation. Methods that rely on soil moisture data can prevent both over-irrigation and water stress, which is particularly vital in areas facing water shortages and competition for resources (Jones, 2004). In precision agriculture, these sensors often form part of a wireless network that continually monitors field conditions. By placing multiple sensors across a field, farmers can capture variations in soil moisture and send this data to a centralized system for analysis. This integration with other information, like weather patterns and crop growth models, facilitates targeted irrigation management and helps farmers make better decisions (Kim *et al.*, 2008) [1, 9, 27, 16, 12, 13]. Recent advancements have improved both the functionality and accessibility of soil

moisture sensors. Now, many of them can connect to the Internet of Things (iot) platforms, allowing farmers to monitor soil conditions remotely through smartphones or computer dashboards. They can even set up automated alerts that notify them when moisture levels drop below a certain threshold, prompting timely irrigation interventions. Plus, advances in data analytics and machine learning help farmers interpret sensor data more effectively, allowing for predictive irrigation management that can really optimize their water use.

2.2 Crop and Plant sensors

Crop and plant sensors have become vital tools in modern farming, significantly impacting the way we approach precision agriculture. These sensors enable continuous monitoring of plant health, growth conditions and responses to stress, providing farmers and researchers with valuable insights for decision-making around irrigation, nutrient management, pest control and yield optimization. Unlike traditional methods that rely on visual inspections and infrequent field visits, these sensors deliver real-time, objective and quantitative data, enhancing the efficiency and accuracy of crop management (Pierce and Nowak, 1999; Zhang *et al.*, 2002). These sensors are designed to measure a variety of plant characteristics, such as chlorophyll content, canopy temperature, biomass, leaf area index and overall crop vigor. These indicators are closely linked to the health and productivity of crops and can signal early signs of nutrient deficiencies, water stress, pest infestations or diseases. By identifying these issues early on, farmers can respond promptly and implement timely interventions that prevent yield losses while optimizing resource use (Hatfield *et al.*, 2008). One of the most common types of crop sensors is the optical sensor. These devices assess plant health by measuring the light reflected off plant canopies. Plants absorb light in the red spectrum for photosynthesis while reflecting near-infrared radiation. The contrast between these reflected values forms the foundation of vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). This index is widely used to estimate plant vigor and photosynthetic activity. These optical sensors can be mounted on handheld devices, tractors, drones or satellites, allowing for versatile and large-scale monitoring of crops (Rouse *et al.*, 1974; Mulla, 2013). Chlorophyll sensors are another important category, measuring the concentration of chlorophyll in plant leaves. Chlorophyll levels are closely tied to nitrogen availability and photosynthetic capacity, making these sensors crucial for nitrogen management in crop production systems. By measuring leaf greenness or spectral reflectance, chlorophyll sensors help farmers determine whether their crops require additional nitrogen fertilizer. This approach not only promotes more precise nutrient management but also reduces excessive fertilizer applications, cutting production costs and lowering environmental pollution (Hatfield *et al.*, 2008). Thermal sensors are also widely utilized in crop monitoring as they measure canopy temperature. The temperature of the plant canopy can provide valuable insights into a plant's water status; typically, water-stressed plants exhibit higher leaf temperatures due to decreased transpiration. Thermal imaging sensors can detect these temperature variations across fields, enabling early identification of water stress and improved irrigation scheduling (Jones, 2004). When integrated with drones or satellites, thermal sensors facilitate rapid assessments of crop water conditions over expansive agricultural areas. Growth and biomass sensors represent another critical group, measuring plant height, canopy structure and crop density. These sensors can utilize technologies such as laser scanning, ultrasonic waves or lidar

systems to gather data on crop growth patterns and biomass accumulation. The information provided by these sensors is crucial for monitoring crop development stages, estimating yield potential and guiding variable-rate input applications in precision farming systems (Mulla, 2013). In recent years, advancements in remote sensing technology have significantly enhanced the scope of crop and plant sensors. Satellite-based and UAV-mounted sensors can collect high-resolution multispectral and hyperspectral data, enabling detailed analysis of crop conditions at various spatial and temporal scales. This capacity allows farmers to monitor large agricultural fields and detect crop stress before it becomes apparent to the naked eye (Doraiswamy *et al.*, 2003; Zhang and Kovacs, 2012). The integration of crop sensors with advanced digital technologies such as wireless sensor networks, the Internet of Things (iot), and machine learning algorithms has further amplified their effectiveness in crop monitoring and management. Sensor data can be transmitted in real time to cloud-based platforms, where sophisticated analytical tools interpret plant health indicators and generate actionable recommendations for farmers. Moreover, machine learning can identify patterns in extensive datasets, enhancing predictions related to crop stress, disease outbreaks and yield outcomes (Liakos *et al.*, 2018; Wolfert *et al.*, 2017)^[19, 27, 10, 21, 18, 12, 6, 26, 14, 25]. Despite the many advantages, implementing crop and plant sensors in agriculture also presents several challenges. Farmers often face high equipment costs, the necessity for proper calibration and maintenance, and the complexities involved in managing large volumes of data generated by these sensors. Environmental factors can further complicate data interpretation, emphasizing the need for continuous learning and adaptation. As technology evolves, staying informed and being flexible will be crucial for farmers harnessing the potential of these innovative tools.

2.3 Climate and environmental sensors

Climate and environmental conditions are integral to the growth, development and productivity of crops. Everyday factors like air temperature, humidity, rainfall, wind speed, solar radiation and atmospheric pressure have a direct impact on plant processes such as photosynthesis, transpiration and evapotranspiration. That's why accurately monitoring these elements is so important for effective crop management and informed decision-making in agriculture today. Climate and environmental sensors have become essential tools, providing real-time data that support precision agriculture and smart farming approaches (Pierce and Nowak, 1999; Zhang *et al.*, 2002). These environmental sensors are often part of automated weather stations or integrated monitoring systems set up in agricultural fields. They continuously gather data on atmospheric conditions and send this information to data loggers or cloud-based platforms for analysis. For instance, air temperature sensors, which typically use thermistors or resistance temperature detectors, measure the ambient temperature, a crucial variable influencing plant metabolism, seed germination and various growth stages. This temperature data also helps calculate growing degree days, which are instrumental in predicting crop development and optimizing planting and harvesting timings (Mulla, 2013). Another key element of these monitoring systems is relative humidity sensors. They measure moisture levels in the air, offering valuable insight into humidity conditions. High humidity can boost the risk of fungal diseases in crops, while low humidity might lead to increased transpiration and water loss from plants. By keeping an eye on humidity, farmers can anticipate disease outbreaks and take preventive measures to

protect their crops (Hatfield *et al.*, 2008). Rainfall sensors, often referred to as rain gauges, are crucial for measuring precipitation levels within the fields. This rainfall data is vital for irrigation planning and managing water resources, especially in rainfed agriculture. When combined with soil moisture data and crop water requirements, farmers can fine-tune irrigation schedules and avoid overwatering (Jones, 2004). Similarly, wind speed and direction sensors which are usually based on anemometers and wind vanes help determine the best conditions for pesticide application while minimizing drift and maximizing efficiency (Gebbers and Adamchuk, 2010). Solar radiation sensors, like pyranometers and light sensors, measure the sunlight intensity that reaches the crop canopy. Understanding solar radiation is vital since it drives photosynthesis, directly influencing crop growth and biomass. Monitoring these levels enables researchers and farmers to evaluate crop productivity and estimate evapotranspiration rates, making it easier to manage irrigation (Campbell and Wynne, 2011). Often, environmental monitoring systems integrate solar radiation data with temperature and humidity measurements to provide a comprehensive picture of the crop microclimate. The rise of wireless sensor networks and the Internet of Things (iot) has revolutionized climate and environmental monitoring in agriculture. Modern sensor networks consist of numerous interconnected nodes that gather data from various locations within a field. These technologies facilitate real-time data transmission and allow for remote monitoring via cloud platforms and mobile apps (Kim *et al.*, 2008; Wolfert *et al.*, 2017). This data-driven approach empowers farmers to respond quickly to shifting environmental conditions. Moreover, climate and environmental sensors are essential for early warning systems that forecast severe weather and climate-related risks. By continuously monitoring conditions, these sensors can spot irregular patterns like heat waves, drought stress or frost events that could jeopardize crops. When paired with predictive models and machine learning algorithms, these sensors greatly enhance our ability to anticipate environmental stress and refine farm management strategies (Liakos *et al.*, 2018). However, despite their many advantages, there are still challenges in the widespread adoption of these sensors in agriculture. Issues around sensor calibration, maintenance, power supply and effective data management remain. Moreover, the variability in local microclimates often necessitates deploying multiple sensors across fields to ensure accurate monitoring (mcbratney *et al.*, 2005). Still, with ongoing technological advancements, environmental sensors are becoming increasingly reliable, affordable, and accessible for farmers [19, 27, 18, 10, 12, 9, 4, 13, 25, 14, 16].

2.4 Remote sensing sensors

Remote sensing sensors have emerged as crucial tools in modern agriculture, helping farmers monitor crop growth, identify stress conditions and enhance farm management practices. Unlike sensors placed on the ground, which offer insights at specific points, remote sensing allows for large-scale observation of agricultural lands using satellites, planes or drones. These technologies gather spectral, spatial, and temporal data, providing farmers and researchers with valuable information about crop health, soil quality and environmental changes. Consequently, remote sensing has greatly improved the efficiency of crop monitoring and enabled data-driven decision-making in agricultural management (Zhang *et al.*, 2002; Mulla, 2013). The way these sensors work is by detecting electromagnetic radiation that is either reflected or emitted from the Earth's surface. When it comes to vegetation, plants react to

sunlight in unique ways they absorb energy in the visible spectrum while reflecting light strongly in the near-infrared range. By analyzing these spectral properties, remote sensing sensors can assess various aspects of plant health, such as vigor, biomass, chlorophyll levels and stress conditions (Campbell and Wynne, 2011). This spectral assessment forms the backbone of vegetation indices like the Normalized Difference Vegetation Index (NDVI), a key tool for evaluating crop growth and productivity (Rouse *et al.*, 1974). Satellite-based remote sensing has been utilized for agricultural monitoring for numerous years. Satellites such as Landsat, MODIS, and Sentinel provide multispectral imagery, allowing for continuous tracking of crop conditions across vast regions. These satellites capture data consistently over time, making it possible to analyze changes in crop growth, identify drought conditions and observe seasonal variability. Moreover, satellite imagery plays a critical role in crop classification, yield prediction and assessing damage from pests, diseases or extreme weather events (Doraiswamy *et al.*, 2003; Lobell, 2013). In addition to satellites, unmanned aerial vehicles (uavs) or drones, have become increasingly important in precision agriculture. Sensors mounted on these drones can capture high-resolution images, enabling detailed monitoring at the level of individual plants or rows. The sensors often include multispectral cameras, hyperspectral sensors, thermal cameras and regular high-resolution RGB cameras. UAV-based remote sensing offers significant advantages over satellite systems due to its flexibility, allowing for timely data collection under favorable conditions (Zhang and Kovacs, 2012). Multispectral sensors capture images across a limited number of spectral bands, often comprising visible and near-infrared wavelengths. These are typically used to compute vegetation indices that reflect the health and nutritional status of plants. In contrast, hyperspectral sensors cover hundreds of narrow spectral bands, offering a more detailed look into plant physiological characteristics and enabling early detection of crop stress (Thenkabail *et al.*, 2018). Additionally, thermal sensors are integral to remote sensing, helping measure canopy temperature, which can reveal plant water stress and assist in optimizing irrigation practices (Jones, 2004). Remote sensing has diverse applications in crop monitoring and management. One of the most significant uses is detecting crop stress due to factors such as nutrient deficiencies, water scarcity, pests and diseases. Signs of stress in plants often appear in their spectral signatures before becoming visually apparent, facilitating early detection and timely corrective actions. Remote sensing is also instrumental in monitoring crop growth stages, estimating biomass and predicting yields, all of which enhance the ability of farmers and policymakers to plan agricultural practices effectively (Hatfield *et al.*, 2008; Mulla, 2013). Another vital aspect of remote sensing is its role in variable rate management within precision agriculture. By analyzing spatial variability in fields, farmers can tailor the application of water, fertilizers, and pesticides to meet the specific requirements of various areas within a field. This practice boosts resource efficiency, lowers production costs, and reduces environmental impacts like nutrient runoff and chemical contamination (Gebbers and Adamchuk, 2010). Recent advancements in digital technologies have further elevated the potential of remote sensing in agriculture. The combination of remote sensing data with geographic information systems (GIS), wireless sensor networks and cloud-based platforms allows for real-time analysis and visualization of crop conditions. Moreover, employing advanced data analytics and machine learning techniques to process extensive volumes of remote sensing data leads to predictive insights that can

significantly benefit crop management (Liakos *et al.*, 2018; Wolfert *et al.*, 2017). Although the advantages of remote sensing technologies are numerous, they also encounter certain challenges. For instance, satellite imagery can be hampered by cloud cover and may have limitations in spatial resolution, while uavs are subject to operational restrictions like battery life and regulatory hurdles. Nevertheless, the continued evolution of these technologies holds great promise for the future of agriculture [27, 18, 4, 21, 6, 15, 26, 12, 10, 18, 9, 14, 25].

3. Wireless Sensor Networks and iot-Based Systems

The integration of wireless sensor networks (wsns) and Internet of Things (iot) technologies has transformed how we approach agriculture. These innovations allow farmers and researchers to gather real-time data from their fields, making it easier to monitor soil health, crop conditions and environmental factors. By connecting various sensors through wireless technology and cloud platforms, wsns and iot create a robust system for smarter farming (Kim *et al.*, 2008; Wolfert *et al.*, 2017). Wsns are made up of multiple sensor nodes placed throughout agricultural fields, measuring important factors like soil moisture, temperature and crop growth. Each node has sensors and communication tools that send data wirelessly to a central hub for analysis. This capability to track different conditions across large areas makes wsns incredibly useful for managing crops effectively (Taneja and Bhatia, 2017). One major benefit of using wsns is their ability to capture the diverse conditions within a field. Traditional monitoring often relies on limited data points, which can miss key variations in soil and crop health. By using many sensor nodes, these networks offer a clearer picture, enabling more precise approaches to irrigation, fertilization, and pest control (Adamchuk *et al.*, 2004; mcbratney *et al.*, 2005). The architecture of these networks comprises three main parts: sensor nodes, communication systems and data processing units. The sensor nodes collect environmental data, while the communication networks, often utilizing technologies like Zigbee and Wi-Fi, transmit this data to a central gateway (Kim *et al.*, 2008). The processing system then analyzes the information, delivering valuable insights to farmers, such as irrigation recommendations or alerts about potential crop diseases (Wolfert *et al.*, 2017). Iot frameworks take things a step further by enabling seamless connections between sensors, devices and digital platforms. In an iot setup, sensors continuously collect data and send it to gateways, which connect to the cloud. Advanced data analytics and machine learning processes this information, presenting it to farmers in a user-friendly way through dashboards and alerts (Zhao *et al.*, 2019; Liakos *et al.*, 2018). Moreover, iot systems allow for automation in farming tasks. For instance, irrigation systems can be triggered automatically when soil moisture levels dip too low or greenhouse conditions can be adjusted based on real-time data. These advancements not only optimize resource use but also make farming more efficient and effective [13, 25, 23, 1, 16, 13, 25, 28, 14].

3.1 Zigbee Technology

Zigbee is a popular wireless communication technology used in agricultural sensor networks and it stands out for its low power consumption, affordability and reliable short-range communication. Based on the IEEE 802.15.4 standard, Zigbee is tailored for low-data-rate wireless networks. In agriculture, you'll often find Zigbee connecting multiple sensor nodes scattered across fields, allowing them to send important data like soil moisture, temperature and humidity back to a central gateway (Taneja and Bhatia, 2017). One of the key benefits of

Zigbee is its mesh networking capability. This feature enables sensor nodes to talk to each other and relay data throughout the network. This multi-hop communication enhances coverage and reliability, especially in extensive agricultural areas where direct connections to a base station may not be feasible. Zigbee has been successfully implemented in applications such as irrigation monitoring and greenhouse management (Kim *et al.*, 2008) [23, 13].

3.2 Wi-Fi Technology

Wi-Fi is another commonly employed wireless communication system in agricultural monitoring applications. It offers high data transmission speeds, making it suitable for environments needing quick transfers of large volumes of sensor data or images. You'll find Wi-Fi-based setups in smart greenhouse monitoring, weather stations and agricultural research facilities where there is reliable internet access (Zhao *et al.*, 2019). Though Wi-Fi provides high bandwidth and dependable connectivity, it typically consumes more power than other wireless options like Zigbee or lora. This higher power demand means Wi-Fi is usually best suited for scenarios where sensors can be connected to stable power sources instead of relying on battery-operated devices. Despite this drawback, Wi-Fi plays a crucial role in linking agricultural sensors with cloud-based platforms and iot systems [28].

3.3 Bluetooth and Bluetooth Low Energy (BLE)

Bluetooth technology, especially Bluetooth Low Energy (BLE), is widely utilized for short-range communication between agricultural sensors and mobile devices. BLE is designed for low energy use, perfect for applications where sensors need to send data to nearby smartphones, tablets or control units. This allows farmers and field technicians to easily collect data directly from sensors during field inspections or equipment maintenance (Liakos *et al.*, 2018). You'll often see Bluetooth in portable agricultural tools like handheld soil moisture meters and environmental sensors. However, its relatively short communication range limits its application in larger field monitoring systems. For this reason, Bluetooth is often used alongside other wireless technologies within integrated iot frameworks [14].

3.4 lora and lorawan Technology

Lora (Long Range) and lorawan are emerging wireless communication technologies gaining traction in precision agriculture. Lora is designed for long-distance communication with minimal power consumption, making it a great fit for monitoring vast agricultural fields. It can transmit data over several kilometers while using very little energy, which is a significant advantage for battery-powered sensor nodes (Wolfert *et al.*, 2017). Lorawan, the network protocol built on lora technology, supports large-scale iot deployments by linking numerous sensor nodes to central gateways. In the agricultural realm, lora networks are commonly employed to monitor soil moisture, weather conditions, and irrigation systems across expansive farming areas. These systems help farmers get real-time updates on field conditions via cloud platforms and mobile applications.

3.5 Cellular Communication Technologies

Cellular technologies like 3G, 4G and the emerging 5G networks also have their place in agricultural monitoring systems, especially for transmitting data from remote fields to centralized servers. Cellular networks provide broad coverage,

enabling agricultural devices to communicate with cloud platforms even from geographically distant locations. These technologies are widely used in smart farming systems requiring remote monitoring and control of irrigation systems, weather stations and autonomous agricultural equipment (Gebbers and Adamchuk, 2010). Cellular communication systems ensure continuous connectivity between agricultural sensors and decision-support platforms, making them particularly suitable for large-scale commercial farming operations. However, the costs associated with data transmission and power consumption can be higher than other wireless technologies, which may limit their application in smaller farming setups [9].

4 Benefits of sensor based crop monitoring

Sensor-based crop monitoring is revolutionizing the way we approach agriculture today. By harnessing real-time data on soil, crops and environmental conditions, these technologies enable farmers to manage their operations more effectively and sustainably. This innovative approach is a cornerstone of precision agriculture, which focuses on managing field variability to enhance efficiency and achieve better results (Pierce & Nowak, 1999; Zhang *et al.*, 2002). One of the key benefits of utilizing sensor-based monitoring is its ability to enhance resource-use efficiency. For instance, soil moisture probes and climate sensors provide continuous updates about water availability and environmental conditions. This allows farmers to fine-tune their irrigation practices, applying water only where and when it's needed. Such targeted irrigation not only conserves water but also significantly boosts water-use efficiency, which is particularly crucial in areas facing water scarcity (Jones, 2004; Gebbers & Adamchuk, ac). Moreover, sensor technologies significantly improve nutrient management. Sensors that assess soil nutrient levels and plant health indicators, such as chlorophyll content, enable farmers to apply fertilizers more precisely. By detecting nutrient deficiencies early, farmers can optimize fertilizer applications applying the right amount at the right time thus cutting input costs and reducing the risk of environmental pollution from over-fertilization. This method supports a more sustainable approach to nutrient management and enhances crop productivity (Adamchuk *et al.*, 2004; Hatfield *et al.*, 2008). In addition, these sensor systems are vital for the early detection of crop stress, pests and diseases. Using plant and canopy sensors alongside remote sensing technologies, farmers can identify small changes in crop health long before visible symptoms manifest. Early intervention enables timely corrective actions, which can prevent crop diseases from spreading and reduce potential yield losses. This proactive strategy improves overall crop health management and decreases the need for pesticides (Mulla, 2013; Liakos *et al.*, 2018). Furthermore, sensor technologies enhance decision-making capabilities. With wireless sensor networks and iot-based systems, farmers can continuously monitor their fields and access real-time information through mobile apps and cloud platforms. Many of these systems come equipped with decision support tools that analyze the data and suggest optimal practices for irrigation, fertilization and pest management. Consequently, farmers can make informed decisions grounded in actual field conditions, rather than relying on guesswork (Kim *et al.*, 2008; Wolfert *et al.*, 2017). These advancements contribute significantly to crop productivity and yield stability. By ensuring that growing conditions are optimized through precise management of water, nutrients and environmental factors, sensor-based systems help maximize crop growth. Early detection of stress conditions further supports improved yield

potential. Research has indicated that technologies related to precision agriculture can substantially boost farm productivity while simultaneously lowering input costs (Bongiovanni and Lowenberg-deboer, 2004). Sensor-based monitoring also plays a crucial role in promoting environmental sustainability. These technologies help minimize excessive use of water, fertilizers and pesticides, thereby reducing environmental degradation, including soil pollution, water contamination and greenhouse gas emissions. Efficient resource management conserves natural resources and fosters sustainable agricultural practices over time (Balafoutis *et al.*, 2017). Additionally, sensor technologies offer insights into the spatial and temporal variability of agricultural fields. By accurately mapping soil properties, moisture levels and crop growth using sensor data, farmers can adopt site-specific management practices. This tailored approach reduces inefficiencies linked to uniform applications and ensures that each section of the field receives the appropriate level of inputs (mcbratney *et al.*, 2005). However, it is essential to recognize that some challenges accompany the adoption of sensor-based systems. Factors such as initial investment costs, technical complexity and the necessity for proper calibration and maintenance may hinder widespread use. Nevertheless, ongoing advancements in sensor technologies and decreasing prices are anticipated to enhance accessibility and encourage more farmers to embrace these innovative solutions in the years to come (Gebbers and Adamchuk, 2010) [19, 27, 12, 1, 10, 18, 14, 13, 25, 3, 2, 16, 9, 16, 1].

5. Limitations

While sensor-based crop monitoring systems offer significant benefits, several challenges impede their broader adoption and effective use in agriculture. These challenges are tied to a mix of technical, economic, environmental and operational factors that need to be addressed to unlock the full potential of these technologies in precision agriculture.

One of the most pressing issues is the high initial investment required for agricultural sensors. Cutting-edge systems like soil sensors, remote sensing devices and integrated Internet of Things (iot) platforms often come with hefty price tags. This financial burden can be particularly daunting for small and marginal farmers, especially in developing regions where resources are scarce. Beyond the upfront costs, farmers also face ongoing expenses for maintenance, calibration and system upgrades, which add to the financial strain (Gebbers and Adamchuk, 2010; mcbratney *et al.*, 2005). Sensor accuracy and calibration pose another significant challenge. The performance of sensors can be affected by environmental variables such as soil types, temperature, salinity and moisture levels. For instance, soil moisture sensors may deliver inaccurate readings if they aren't calibrated properly for the specific conditions of the soil they're measuring. Similarly, optical sensors that monitor crops can be influenced by changes in lighting, atmospheric conditions and background noise. These variations can lead to errors in data collection and interpretation, which in turn can affect the quality of decision-making processes (Adamchuk *et al.*, 2004; Mulla, 2013). Data management and integration are also major hurdles for sensor-based technologies. Modern agricultural sensors generate vast amounts of data that need to be stored, processed and analyzed effectively. Handling these large datasets requires advanced computational resources, cloud infrastructure and skilled personnel. Moreover, combining data from various sensors and systems can be complicated due to differences in data formats, communication protocols and overall compatibility. The lack of standardization among sensor

technologies further complicates the integration process (Wolfert *et al.*, 2017). Power supply and energy management remain critical challenges, particularly for wireless sensor networks placed in remote agricultural areas. Many sensors depend on batteries, which often need frequent replacement or recharging. Managing a dependable power supply in extensive deployments can be both challenging and costly. While renewable energy sources like solar panels are becoming more common, their effectiveness can be limited by environmental conditions, impacting their performance in certain regions (Kim *et al.*, 2008). Connectivity issues further complicate the effective use of sensor-based monitoring systems. Reliable internet and communication networks are crucial for real-time data transmission and remote monitoring. Yet, in numerous rural and remote agricultural areas, network coverage can be spotty or unreliable. This inconsistency can lead to data delays or losses, reducing the efficiency of sensor systems and hindering timely decision-making (Taneja and Bhatia, 2017). Another hurdle is the technical complexity of employing these sensor systems. Farmers often need specific training and technical knowledge to install, operate and maintain these technologies effectively. A lack of expertise and awareness among farmers can prevent the successful adoption of sensor technologies. Additionally, interpreting sensor data and turning it into actionable insights often requires specialized knowledge or decision-support tools that may not always be readily available (Liakos *et al.*, 2018). The environmental durability and reliability of sensors are also significant concerns. Agricultural settings can be harsh, exposing sensors to dust, moisture, extreme temperatures and physical damage during field operations. These conditions can affect sensor performance and lifespan, leading to frequent maintenance or the need for replacements. Ensuring that sensors are robust and durable is essential for their extended use in agricultural environments (McBratney *et al.*, 2005). Finally, data privacy and security issues are becoming increasingly important in the context of sensor-based agriculture. As farm data is increasingly stored and transmitted through cloud platforms, there are growing risks associated with unauthorized access, data breaches and the potential misuse of information. Addressing concerns related to secure data transmission and protecting farmers' data rights is vital for the sustainable adoption of these technologies (Wolfert *et al.*, 2017) [16, 1, 18, 25, 13, 23, 14].

6. Future prospects

The rapid advancement of sensor technologies, alongside innovations in digital agriculture, presents a remarkable opportunity to revolutionize crop monitoring and management. As the agricultural sector grapples with increasing challenges from climate change, a burgeoning population, and limited resources, the role of sensor-based systems becomes ever more crucial. These technologies have the potential to enhance sustainable and efficient food production, but several research gaps and obstacles need to be addressed to unlock their full potential. One of the most exciting future directions in this field is the development of low-cost and high-precision sensors. Currently, while existing sensor technologies can deliver accurate and reliable data, their prohibitive costs often prevent smallholder farmers from adopting them. To make these tools accessible, future research should prioritize the design of affordable, scalable sensor solutions that do not sacrifice accuracy or durability. By harnessing advances in nanotechnology and microelectronics, we can create compact and energy-efficient sensors that can be widely used in agriculture, opening up new avenues for productivity. Another

critical focus area is the integration of multiple sensor data sources. Modern farming practices generate an abundance of data from various sensors ranging from those monitoring soil conditions to those keeping track of climate patterns and remote sensing technologies. However, the challenge lies in synthesizing these diverse datasets into a cohesive framework. Research efforts should aim to establish standardized protocols and advanced data fusion techniques to blend information from different sensor types. This integration will enable farmers to gain a holistic view of crop conditions, which in turn enhances decision-making accuracy and facilitates more precise, site-specific management strategies. The intersection of artificial intelligence (AI) and machine learning (ML) with sensor technology also holds immense promise for the future of agriculture. AI models can process vast amounts of sensor data to uncover patterns, predict crop stress and optimize farm management practices. Future endeavors should concentrate on creating robust and scalable AI models that can adapt to various field conditions, ultimately providing farmers with trustworthy recommendations. Moreover, improving the interpretability of these AI models is essential and outputs must be understandable and actionable for farmers, ensuring that the technology serves them effectively. Additionally, the integration of sensor technologies with automation and robotics is on the horizon to revolutionize farming practices. Imagine autonomous systems like robotic sprayers, drones and automated irrigation systems utilizing real-time sensor data to carry out precise agricultural tasks with minimal human involvement. This synergy can significantly boost labor efficiency, cut down on resource wastage and enhance crop yields. However, ongoing research is necessary to strengthen the reliability, scalability and affordability of these integrated systems.

A vital area that requires attention is the calibration and standardization of sensors. The performance of these devices can vary widely based on factors such as environmental conditions, soil types and specific crop characteristics. Inconsistent calibration procedures can result in unreliable data, undermining the effectiveness of sensor-based systems. Future research must focus on developing reliable calibration methods and establishing industry standards to ensure that measurements are consistent and accurate across different agricultural contexts. Connectivity and infrastructure limitations pose significant challenges, especially in rural and remote regions. Reliable internet access and communication networks are vital for real-time data transmission and the successful implementation of IoT-based applications. Future initiatives should work towards developing low-power, long-range communication technologies to enhance connectivity in rural areas, thereby supporting the effective deployment of sensor networks. Technologies like LoRaWAN and satellite-based communication systems could be instrumental in overcoming these connectivity issues. As we navigate the rise of sensor-based agriculture, concerns surrounding data management, privacy and security are becoming increasingly prominent. With vast amounts of agricultural data being collected and stored in cloud platforms, ensuring data protection and secure access is crucial. Future research must tackle issues related to data ownership, privacy policies and cybersecurity to foster trust among farmers and other stakeholders. Finally, there exists a critical gap in the adoption of sensor technologies among farmers, especially in developing countries. Various barriers, including a lack of awareness, technical know-how and access to training programs, hinder effective utilization of these technologies. Promoting extension services, capacity-building initiatives and developing

user-friendly interfaces are essential to encourage farmers' adoption of new technologies. Additionally, future research should explore the socio-economic aspects of technology usage, including comprehensive cost-benefit analyses to demonstrate the real value these innovations can bring to farming communities.

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