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Innovative Sensor Technologies in Agriculture- Applications and Challenges: A Review

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ABSTRACT

The integration of Internet of Things (IoT) technologies has advanced agriculture by enabling precision farming and promoting sustainability. IoT sensors collect real-time data on environmental conditions, soil moisture, pH and nutrients. Combined with AI tools, they support informed decision-making, improve productivity, optimize resources and contribute to carbon-neutral practices. This review classifies sensors by principles, energy needs, materials, applications and detection methods, emphasizing their role in IoT-based agriculture. A fertigation case study illustrates IoT impact through AI-integrated sensors and automation, while addressing adoption challenges. The case study was conducted in regional agricultural research station (South Zone), Vellayani, Thiruvananthapuram, during 2222-23 with the funding from the Kerala State Planning Board. The review supports sensor understanding and selection for carbon-zero agriculture technologies, though challenges in large-scale adoption remain and need to be addressed.

Key words: Carbon-neutral farming, Internet of things (IoT), Precision agriculture, Sensor classification.

A sensor is a device or module that detects physical events or changes and transmits the data to a processor for analysis (Paul *et al.,* 2022). It converts phenomena like light, temperature, or pressure into measurable signals, typically digital (Javaid *et al.,* 2021). As shown in Fig 1, a sensor comprises a sensing unit, conversion unit and output unit (NMAB, 1995). The sensing unit detects the parameter, the conversion unit transforms it into an electrical signal and the output unit processes and transmits it, possibly including amplification or analog-to-digital conversion.

Advancements in sensors have improved performance, reliability and miniaturization across fields such as medicine, engineering and agriculture (Zhang *et al.,* 2023b). Recent developments include AI and ML integration (El Khediri *et al.,* 2024), low-power sensors, edge computing for real-time processing (Oliveira *et al.,* 2024) and wireless communication *via* Bluetooth, Wi-Fi and LoRaWAN (Ketshabetswe *et al.,* 2019). These advances, along with lower costs, have increased accessibility and ease of deployment.

Sensors are central to IoT systems and are widely used in agriculture, healthcare, transportation and smart cities (Poongodi *et al.,* 2020; Chataut *et al.,* 2023; Gubbi *et al.,* 2013). They enable real-time data collection, supporting productivity and sustainability in agriculture by optimizing fertilizer, pesticide and water use through monitoring soil and crop conditions (Roper, 2021). They also help mitigate environmental stress and pest outbreaks, improving yields and reducing losses (Rajak *et al.,* 2023).

Sensor performance in agriculture is defined by static and dynamic characteristics. Static parameters include accuracy, resolution, sensitivity, linearity and drift (Vyas and Thakur, 2020; NMAB, 1995). Dynamic characteristics describe time-based responses-zero-order systems respond instantly, first-order systems approach output gradually and second-order systems may oscillate before stabilizing (Selvolini and Marrazza, 2023). Sensors may be active or passive, depending on whether they require external input.

Understanding these characteristics is key to selecting appropriate sensors for IoT applications (Patel *et al.,* 2020). Classification of sensors-by measured parameters (*e.g.*, temperature, pressure), operating principles (*e.g.*, resistive, capacitive), or application domain-supports optimal selection, performance benchmarking, integration and scalability. It also provides a structured framework for

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researchers to explore sensor functionality and trade-offs, enhancing innovation and usability.

Classification of sensors used in agriculture

Sensors in agriculture are categorized by working principle, energy requirements, materials, detection methods and applications (Sajja and Bhowmik, 2023). Key types include resistive, proximity, inductive, optical, electric and biosensors. Strain gauges, a type of resistive sensor, alter resistance under mechanical stress and are used to assess structural integrity of agricultural buildings (Yoder and Adams, 2022). Capacitance proximity sensors evaluate harvest yields, while inductive proximity sensors detect ferromagnetic materials in soil (Moheimani *et al.,* 2022). Optical sensors, such as photodetectors, convert light into electrical signals, enabling calculation of vegetation indices for assessing crop vigor and growth dynamics (Candiago *et al.,* 2015). Devices like SPAD and ClorofiLOG require direct leaf contact for measurements (Jurisic *et al.,* 2021). Electrical sensors measure soil properties like resistance and capacitance; for instance, soil electrical conductivity sensors assess field variability, potentially replacing detailed lab analyses (Visconti and de Paz, 2016). Electric and electromagnetic soil sensors are valued for rapid response, low cost and durability (Gupta *et al.,* 2019).

Biosensors detect toxins and pathogens, aiding in continuous crop monitoring and early disease detection (Wang *et al.,* 2022). Immunosensors, utilizing antibodies or antigens, rapidly detect pesticide residues (Jeevula and Sireesha, 2021). Chemical sensors measure properties like NPK levels, pH and gas concentrations, ensuring optimal nutrient ratios for crops (Agrahari *et al.,* 2021).

Based on energy requirements, sensors are classified as active or passive. Active sensors, such as RADAR, GPS and LiDAR, emit signals and require external power (Mulindi, 2023). LiDAR provides three-dimensional data on crop health and terrain (Farhan *et al.,* 2024). Passive sensors, like thermocouples, generate signals directly from environmental changes; for example, infrared thermocouples measure leaf temperature to assess plant physiological states (Cheng *et al.,* 2020).

Advancements in materials and technology have led to the development of CMOS, infrared, ultrasonic, microwave, electromechanical, radar, electrochemical and MEMS-based sensors (White, 1987). CMOS image sensors, combined with infrared proximity sensors, have been used for wildlife monitoring (Camacho *et al.,* 2017). Ultrasonic and microwave technologies are employed in food processing and obstruction detection (Singla and Sit, 2021; Bhargava *et al.,* 2021).

Sensors are also categorized by output signals: analog or digital. Analog sensors, like thermal remote sensors, estimate soil and crop water stress, detect diseased crops and map soil texture (Khanal *et al.,* 2017). Digital sensors, such as thermometers, provide discrete outputs; for instance, infrared photodiode thermometers enable long-term, contactless monitoring of cattle body temperature (Murugeswari *et al.,* 2022).

In agricultural applications, sensors monitor parameters like soil moisture, temperature, humidity and crop conditions. Adoghe *et al.* (2017) developed a solar-powered automated weather station with meteorological sensors to support agricultural decision-making. Palaparthy *et al.* (2018) created a low-cost graphene oxide humidity and soil moisture microsensor for in-situ field measurements. An automatic rain sensor helps farmers protect their crops from unexpected sudden rains during post-harvest operations (Rajesh, 2019). Smart Environment Monitoring systems incorporate sensors like gas and particulate matter sensors for air quality assessment (Ullo and Sinha, 2020). Electronic nose and electronic tongue have a wide range of application in the food and dairy industry (Heema and Gnanalakshmi, 2022). Raina *et al.* (2024) developed an energy-efficient device for monitoring onion quality using gas, temperature and humidity sensors. Application of GPS sensors in precision agriculture is given Table 1.

Operating principles of sensors in modern agriculture

Sensors operate based on principles such as amperometric, capacitive, pressure, MEMS, piezoelectric, thermochemical, inductive, magnetic, thermoelectric, optical, ultrasonic, radiometric, flexible and nanotechnology. Amperometric sensors measure current from enzymatic reactions; for example, they detect algal toxins in water (Wu *et al.,* 2019) and ethylene in agricultural products (Caprioli and Quercia, 2014). Capacitive sensors detect changes in capacitance; Kulmány *et al.* (2022) developed an automated capacitive soil moisture sensor. A soil moisture meter based on a capacitive type sensor is calibrated by Balaji and Pandiarajan (2022) for sandy clay loam soil conditions.

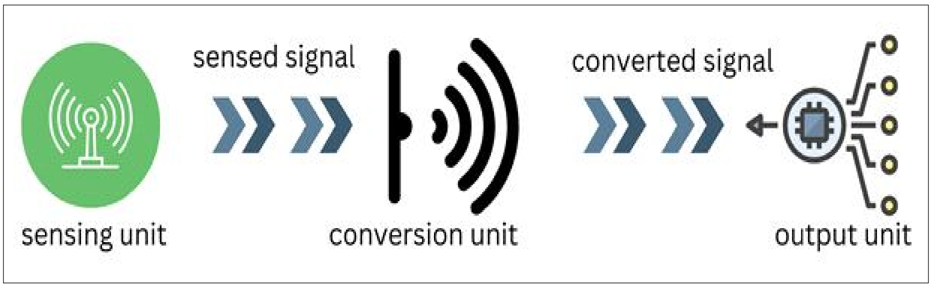

Fig 1: Components of a sensor.

Pressure sensors convert pressure into electrical signals and are essential in monitoring fluid or gas pressure in various systems. MEMS sensors integrate mechanical and electronic components on a microscale, allowing cultivation of plants under different stress conditions and monitoring plant-pathogen interactions (Sharma *et al.,* 2019). Piezoelectric sensors generate electric charge under mechanical stress and are used in precision seeders to detect impacts (Rossi *et al.,* 2023).

Chemical sensors detect chemical compounds through interactions leading to changes in physical properties; they are used in gas leak detection and environmental monitoring (Wang, 2016). Inductive sensors operate on electromagnetic induction to detect metal objects and are applied in soil water content prediction (Kachanoski *et al.,* 1988). Magnetic sensors detect changes in magnetic fields based on the Hall effect or magnetoresistance and are used in position sensing and speed detection (Elzwawy *et al.,* 2024).

Thermoelectric sensors, like thermocouples, convert heat to electric energy and are used in temperature measurements .Optical sensors detect changes in light properties and are applied in imaging systems; hyperspectral sensors capture light across wavelengths for crop health assessment (Lu *et al.,* 2018). Infrared sensors are used in non-destructive testing and precision diagnostics in agriculture (Bhan and Dhar, 2019).

Ultrasonic sensors use sound waves to detect objects and measure distance, aiding in irrigation systems for precision agriculture (Camacho *et al.,* 2022). Beyaz and Gerdan in 2020, reported the use of ultrasonic sensors for the classification of potato. LiDAR technology provides precise 3D data for crop health and terrain analysis (Rivera *et al.,* 2023).

Sensor fabrication approaches and material-based classification for agricultural applications

Sensor development is significantly influenced by the choice of materials and fabrication techniques, which determine sensitivity, durability and application scope. Advanced materials such as nanomaterials, polymers, silicon and graphene have improved sensor performance (Bhandari *et al.,* 2023). Nanomaterials, characterized by high surface area and distinct electrical properties, are commonly used in chemical and biological sensors to enhance sensitivity and selectivity (Laxmi *et al.,* 2022). Integration of nanoscale mechanical devices with nanoelectronics has expanded research in sensor-based systems (Wang, 2024). In agriculture, nanomaterials improve crop productivity and soil health, influence pollutant behavior and are utilized in both biotic and abiotic remediation strategies (Usman *et al.,* 2020). They enhance nutrient uptake efficiency and support early disease detection. Silver and iron nanoparticles are applied for disinfection in livestock and poultry operations. Nanosensors, including smart dust and gas sensors, provide rapid environmental pollution assessment (Chakraborty *et al.,* 2024). Nano biosensors detect pathogens, fertilizers, soil pH and moisture, contributing to reduced dependence on chemical inputs and optimized nutrient use (Kaushal and Wani, 2017). Electrochemical, voltammetric and amperometric nanosensors have been developed for detecting pathogenic bacteria (Ahmed and Patel, 2023).

Polymers offer stretchability, conductivity and biocompatibility, making them suitable for wearable sensors. A chitosan-based water ink enables fabrication of stretchable strain sensors through direct application and

Table 1: Applications of GPS sensors in precision agriculture.

Application	Description
Precision crop planting	Precise guidance of agricultural machinery for seeding and planting crops.
Soil mapping and sampling	Soil sampling and mapping; optimizing fertilization and irrigation.
Autonomous tractor navigation	Tractors follow pre-defined paths or use real-time data, reducing manual labor and increasing efficiency.
Livestock tracking	Sensors track livestock movement and location, supporting herd management, detecting health issues and preventing theft or loss.
Variable rate application	Variable rate technology optimizes fertilizer and pesticide application based on soil and crop conditions, reducing waste and environmental impact.
Yield monitoring	Harvesters monitor crop yields in real time, aiding yield analysis and planting decisions
Irrigation management	Precision irrigation applies water efficiently and only where needed, reducing usage and enhancing crop health.
Field boundary mapping	Mapping field boundaries, optimizing land management and regulatory compliance
Weather data collection	Weather stations gather real-time field-specific weather data, aiding farmers in decision making and risk assessment.
Pest and disease mapping	Sensors monitor pest and disease spread, allowing targeted interventions and reducing broad spectrum treatments.
Asset tracking	Track and manage agricultural assets to optimize use and reduce theft or loss.
Environmental monitoring	Monitor soil moisture, temperature and humidity, promoting sustainable agriculture and resource conservation.

drying at room temperature, producing sensors with a gauge factor of 64 for strains between 1% and 8% and stretchability up to 60%. These can be directly applied to plant surfaces, allowing in-situ fabrication and reducing energy and time requirements (Presti *et al.,* 2024). Wearable sensors enable continuous, real-time monitoring of plant physiological biomarkers, translating microenvironmental signals into electrical outputs (Carella *et al.,* 2024; Chen *et al.,* 2023). Graphene, with high electrical conductivity, flexibility and mechanical strength, is suitable for flexible sensors and high-performance electronics (Nag *et al.,* 2018; Alam *et al.,* 2022; Lau, 2023).

Silicon remains the core material in sensor manufacturing, particularly in MEMS devices where it facilitates miniaturization and electronic integration (Le *et al.,* 2021). 3D printing allows rapid prototyping of sensors with complex geometries and multi-material integration (Khosravani and Reinicke, 2020). MEMS sensors are fabricated using microfabrication techniques such as photolithography and etching, which provide precise microscale control over sensor features and are essential for mass production of semiconductor devices. Molecular imprinting is employed to produce highly selective sensors by forming polymer matrices with molecular recognition sites, enhancing their specificity for target molecules in chemical and biological sensing (Dong *et al.,* 2023). Advances in these fabrication techniques and materials have enhanced the performance, scalability and application scope of next-generation sensors (Hossain *et al.,* 2024a, b).

Leveraging sensors for carbon-neutral agricultural systems

IoT sensors enable real-time monitoring of soil moisture, pH and nutrients (Basnet and Bang, 2018). Environmental sensors assess air, water and soil quality (Narayana *et al.,* 2024; Bainomugisha *et al.,* 2024), helping reduce pollution and anthropogenic impact (Bansal *et al.,* 2022). Sensor-based irrigation systems improve field water management (Vandome *et al.,* 2024). Thermal infrared and microwave sensors on satellites estimate crop temperature, water stress and soil moisture (Sishodia *et al.,* 2020).

Hyperspectral sensors capture crop stress responses across wavelengths (Chakhvashvili *et al.,* 2024), supporting pest/disease detection and IPM strategies (Terentev *et al.,*

Table 2: Major types of sensors and their features.

Sensor type	Feature	Example	Model number
Amperometric	Measures current related to substance oxidation	Clark oxygen sensor	DO220 (Clark)
Capacitive	Senses changes in capacitance	Capacitive soil moisture sensor	SONOFF MS01, Terros 12 series
Chemical	Detects chemical changes	Electrochemical gas sensor	MQ-9 gas sensor
Colour	Senses color variations	RGB color sensor	TCS3200
Flexible	Adapts to curved surfaces	Graphene-based flexible sensor	Graphene GO
Image	Captures visual data	CMOS image sensor	CMOS OV7670
Inductive	Detects metal presence	Inductive proximity sensor	LJ12A3-4-Z/BX
Infrared	Detects heat signatures	Passive infrared sensor (PIR)	IR GP2Y0A21YK0F
Laser	Measures distance	LIDAR sensor	Hokuyo UST-10LX
Level	Monitors fluid levels	Ultrasonic level sensor	HC-SR04
Light	Senses light intensity	Photodiode light sensor	LDR GL5528
Location	Provides positional data	GPS sensor	GPS NEO-6M
Magnetic	Senses magnetic fields	Hall effect sensor	A1302 Hall Effect
MEMS	Microelectromechanical system	MEMS accelerometer	MPU6050
Motion	Detects movement	Motion detection sensor	PIR HC-SR501
Multimodal	Integrates multiple sensing types	Multimodal environmental sensor	BME680
Nano	Nanotechnology enhanced sensitivity	Carbon nanotube sensor	CNT Nanosensor
Optical	Measures optical properties	Fiber optic sensor	Fiber Bragg Grating
Piezoelectric	Generates electricity from pressure	Piezoelectric vibration sensor	Murata 7BB-20-6L0
Pressure	Detects pressure variations	Piezoresistive pressure sensor	BMP280
Proximity	Detects nearby objects	Capacitive proximity sensor	Capacitive TTP223
Relay	Controls circuits	Solid state relay	Solid State Relay
Resistive	Changes resistance with force	Resistive touch sensor	FSR 400
Servo	Controls position	Servo motor with position sensor	MG996R
Solar	Converts solar energy	Solar photovoltaic sensor	SP3-37
Temperature	Measures temperature	Thermistor	DS18B20
Ultrasonic	Measures distance using sound waves	Ultrasonic distance sensor	MaxBotix MB7360

2022). Sensor networks provide early warning of plant diseases (Singh *et al.,* 2020). Tools like FP-XRF detect heavy metals in soil; other devices capture soil strength and moisture (Mcgrath and Scanaill, 2013). IoT trackers verify carbon emissions (Peng *et al.,* 2024) and help manage livestock waste (Zakirova *et al.,* 2022). MEMS/NEMS technologies support nutrient and salinity monitoring (Palaparthy *et al.,* 2013). NPK sensors allow precise nutrient application (Ameer *et al.,* 2024).

Flexible proximity sensors using PDMS and PI overcome traditional design limitations. Fe_3O_4 nanoparticles enhance sensitivity (Jin *et al.,* 2023). Amperometric sensors detect ethylene to monitor ripening (Caprioli and Quercia, 2014). AI, ML and IoT assist in predictive disease detection (Delfani *et al.,* 2024), drone-assisted health monitoring and automated machinery deployment (Chamara *et al.,* 2022). Sensor data supports precise agrochemical use (Basnet and Bang, 2018). Hemming *et al.* (2019) used sensors to monitor crop and environment parameters in greenhouses. Table 2 decpits major type of sensors and their features.

Electronic integration of sensors in agricultural systems: A case study

India's agriculture faces constraints due to climate, urbanization and outdated practices. Fertilizer misuse degrades soil. Monitoring temperature, pH, moisture, EC and NPK is vital for yield. Optimal pH (6.5–7.0), moisture and nutrient levels support healthy crops. Technologies incorporating microcontrollers and wireless systems enable precision farming (Chamara *et al.,* 2022).

In a smart nursery system, sensors monitor conditions; edge computing supports local decisions. Fig 2 and Table 3. Actuators manage fertigation through drip and mist systems. Filtered data is sent to the cloud for analytics. NPK, pH, EC, temperature and humidity sensors inform decisions. Soil moisture at 60-70% optimizes yield and appearance, while low moisture increases pH and lowers quality. The system enables efficient resource use and remote control. The case study was conducted in Regional Agricultural Research Station (South zone), Vellayani, Thiruvananthapuram, during 2222-23 with the funding from the Kerala State Planning Board.

Operational constraints in the adoption of sensors

Sensor accuracy is affected by temperature, humidity and salinity (Zhang *et al.,* 2023c; Ariyaratne *et al.,* 2023; Qi *et al.,* 2024). Clay soils reduce moisture sensor reliability (Corwin and Scudiero, 2016). Sensors in autonomous systems fail in bad weather (Vargas *et al.,* 2021). Calibration, interference and power efficiency limit performance. Flexible sensors sacrifice electrical performance for adaptability (Zhou *et al.,* 2022). Cross-sensitivity impacts data accuracy. Interoperability and power access are critical for IoT deployment (Soussi *et al.,* 2024). SERS biosensors need improvement to avoid interference (Tang *et al.,* 2024).

Adoption challenges include environmental impacts on lifespan, lack of interoperability, energy limitations, poor

Table 3: Components of the smart fertigation system.

Component name	Purpose
Node 32	Microcontroller unit wherein edge computing takes place.
Cloud Storage	Storage of selected data for further processing using ML techniques.
Relays	Control the various pumps.
Tanks	Separate tanks for storage of water, nitrogen, phosphorous and potassium.
NPK 7 in 1 soil sensor	Obtains real-time values of N, P, K, EC, pH, soil moisture and soil temperature.
Temperature sensor	Detects atmospheric temperature in real-time.
Humidity sensor	Detects atmospheric humidity in real-time.

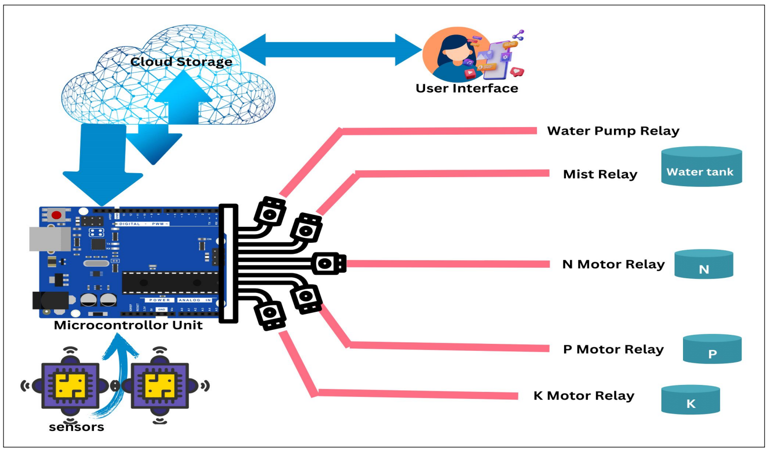

Fig 2: Work flow diagram of the smart fertigation system.

rural connectivity, cost barriers and inconsistent performance across crops and landscapes. Other issues include interference, incomplete datasets, scaling difficulties, complex data storage, low farmer training, policy gaps, data security and low ROI. Research into sustainable sensor materials is needed to meet food security goals.

Emerging trends in sensor technology

Sensor development is moving toward AI/ML-enabled smart sensors for real-time decisions. These technologies enhance automation and predictive control but raise security and power issues. Future trends include edge computing, quantum sensing, 5G and improved integration (Rajora *et al.,* 2024). Nanostructured materials and miniaturization improve performance (Ahmad *et al.,* 2024). Flexible and wearable sensors will grow in medical, environmental and agricultural domains. Research focuses on sensor compatibility, performance and sustainability.

CONCLUSION

IoT sensors enhance precision agriculture through real-time monitoring, input optimization and environmental tracking. Categorized by characteristics and applications, they help manage soil, water and crop health. Sensors shift agriculture from traditional to data-driven systems. Selection based on accuracy and reliability is crucial. Adoption is limited by cost, energy and security concerns. Future directions include AI-enabled, multi-functional sensors and integrated platforms.

Sensors support sustainable agriculture by increasing efficiency and yield while reducing environmental impacts. Advancements in AI, ML, edge computing and quantum sensing will expand their capabilities. Continued research into energy-efficient, secure sensor systems is essential for broader application.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee. (No animals used).

Conflict of interest

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