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The Biophysics of Precision Agriculture: Smart Sensors and Materials for Sustainable Farming: A Review

Thodangi Rajya Lakshmi[1#], Bindu Ambaru[2#]

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ABSTRACT

The rising global demand for food, coupled with the challenges of climate change, necessitates the adoption of advanced technologies to enhance agricultural productivity and sustainability. Precision agriculture, powered by innovative sensor technologies, is transforming farming by enabling real-time monitoring of crops, soil and environmental conditions. These sensors play a crucial role in optimizing resource utilization, improving yields and minimizing environmental impact. This paper explores key sensor technologies used in agriculture, including electrochemical sensors for plant health assessment, hyperspectral and multispectral sensors for crop analysis, infrared (IR) and LiDAR sensors for environmental mapping and soil moisture sensors for precision irrigation. Additionally, mechanical sensing technologies, temperature and humidity sensors (TMS) and biosensors, such as surface plasmon resonance (SPR) sensors, are examined for their role in disease detection, food safety and environmental monitoring. Despite advancements in agricultural sensors, no single manuscript comprehensively lists all materials used in their fabrication. This paper highlights the critical role of materials, such as carbon nanotubes, graphene, metal oxides, conductive polymers and biocompatible composites, in improving sensor sensitivity, durability and efficiency that can be adapted for long-term agricultural applications. Furthermore, this review provides valuable insights into the role of advanced materials in agricultural sensor development, emphasizing the need for flexible, durable and highly sensitive plant sensors. This comprehensive analysis aims to guide researchers in developing next-generation agricultural sensors that enhance real-time monitoring, improve efficiency and promote sustainable farming practices.

Key words: Materials, Sensors, Smart farming, Sustainable agriculture.

Agriculture today is facing unprecedented challenges due to the growing global demand for food, shrinking arable land, resource limitations and the unpredictable impacts of climate change. These pressures have catalyzed a shift toward smarter, more sustainable farming practices. Precision agriculture has emerged as a transformative approach, leveraging sensor-based technologies to enable data-driven decision-making, optimize input use and enhance crop productivity while minimizing environmental impact (Getahun *et al*., 2024).

Sensors form the backbone of smart farming practices, with applications spanning soil health monitoring, crop growth assessment, stress and disease detection, water resource management, environmental condition tracking and contaminant detection (Kerry and Escolà, 2021). By providing real-time, site-specific data, sensor technologies empower farmers to respond swiftly to dynamic field conditions, thereby reducing input costs, preventing crop losses and enhancing overall sustainability (Ambaru *et al*., 2025). Their integration into agricultural systems offers several critical benefits, including improved productivity through early detection of nutrient deficiencies, pests and diseases; optimized use of water, fertilizers and pesticides; and better environmental outcomes through the reduction of runoff, soil degradation and greenhouse gas emissions. In this context, the digital initiatives of the Indian Council of Agricultural Research further enhance these benefits by improving access to agricultural information, strengthening research capabilities and supporting technology-enabled education across the country (Sharma and Tiwari, 2023). Furthermore, sensors contribute to higher crop quality and food safety by enabling the early identification of contaminants and abiotic stressors. Altogether, these advantages facilitate data-driven, precision agriculture aimed at achieving long-term sustainability and resilience in modern farming systems (Steeneken *et al*., 2023).

Several types of sensors are employed in agriculture to achieve precise monitoring and management of crop and environmental parameters. Electrochemical sensors are widely used to detect key soil and plant analytes, including pH, nutrient ions and agrochemical residues, providing essential information for soil fertility and plant nutrition management (Kim and Lee, 2022). Optical

[1]Department of Physics, Sardar Patel College, Secunderabad-500 025, Telangana, India.
[2]Department of Life Sciences, Sardar Patel College, Secunderabad-500 025, Telangana, India.
[#]Authors contributed equally for the work.

Corresponding Author: Bindu Ambaru, Department of Life Sciences, Sardar Patel College, Secunderabad-500 025, Telangana, India. Email: bindu.ambaru@gmail.com

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sensors, such as hyperspectral and multispectral systems, enable non-invasive assessment of plant health, canopy structure and photosynthetic activity (Obeid *et al*., 2021). Mechanical sensors monitor parameters like plant turgor, stem diameter and root activity, offering insights into physiological stress and growth dynamics (Phan *et al*., 2024). Temperature and humidity sensors help regulate the microclimate within agricultural environments, supporting disease prevention and optimizing conditions for plant metabolism (Ikram *et al*., 2024). Biosensors, including Surface Plasmon Resonance (SPR) devices, provide early detection of biotic stressors such as pathogens and toxins, contributing to improved crop protection and food safety (Zhao *et al*., 2020). Location sensors, along with air and mass flow sensors, facilitate site-specific field management, spatial mapping and targeted application of agricultural inputs (Aarif *et al*., 2025). Additionally, soil moisture sensors play a critical role in irrigation management by ensuring optimal water delivery and preventing both over- and under-irrigation (Lloret *et al*., 2021). A recent review (Geetha *et al*., 2025) emphasizes the role of innovative sensor technologies in promoting carbon-zero agricultural practices. Together, these sensor technologies form the basis of precision agriculture, enabling enhanced productivity, sustainability and resource efficiency. These diverse types of sensors used in agriculture are strategically positioned across various zones of the field-embedded in the soil, mounted on plants, integrated into irrigation systems, or deployed via drones and satellite platforms-depending on their specific functions, such as monitoring soil conditions, assessing plant health, detecting environmental changes, or guiding resource application, thereby enabling comprehensive and site-specific farm management.

While extensive research has been dedicated to the development and application of these sensor types, less attention has been given to the materials that form the backbone of sensor performance. The sensitivity, durability and efficiency of sensors are largely determined by the materials used in their construction. Innovations in materials science have introduced a range of high-performance materials such as carbon nanotubes, graphene, metal oxides, conductive polymers and biocompatible composites, which offer enhanced electrical, optical and mechanical properties suited for rugged agricultural environments (Hossain *et al*., 2024).

This review aims to bridge the gap between agricultural sensor technologies and material science by providing a comprehensive overview of key sensor types and the advanced materials used in their fabrication. In addition to summarizing recent developments, it also offers critical insights into existing challenges, material limitations and future research directions to guide the design of next-generation sensors that are flexible, robust and sustainable for long-term agricultural applications.

Smart sensors and materials for sustainable farming

The integration of smart sensors developed from advanced materials is transforming sustainable farming practices. Fig 1 demonstrates the placement of various sensors on plants and across agricultural fields, highlighting their role in real-time monitoring and precision management.

Optical sensors

Optical sensors are crucial tools in modern agriculture, enabling non-invasive and non-destructive measurement of various physical and chemical properties of plants and soil through light-based techniques (Ferreira *et al*., 2017) Key parameters assessed include soil moisture, nutrient concentrations, chlorophyll content and plant stress indicators via measurements of reflectance, transmittance, fluorescence and absorption (Talal *et al*., 2024). Optical sensing informs critical crop management decisions such as irrigation, fertilization and pesticide application, supporting precision agriculture practices (Lee *et al*., 2010).

Selection of light wavelengths underpins remote sensing: visible light tracks crop growth, infrared detects water status and stress and shortwave infrared supports soil and biomass assessment (Talal *et al*., 2024). Multispectral and hyperspectral imaging (MSI, HSI) enable early disease detection by distinguishing subtle spectral changes before symptoms appear (Lee *et al*., 2010). Fluorescence and infrared spectroscopy further aid stress detection, both *in situ* and *via* UAVs or satellites. Drone-mounted sensors (MSI, HSI, LiDAR) deliver high-resolution insights into crop health, soil fertility and input optimization, while ground sensors complement by monitoring soil moisture and microclimate. Together, active (*e.g*., LiDAR) and passive (*e.g*., reflectance imaging) RS technologies provide spatial-temporal data crucial for early stress and disease detection (Bi *et al*., 2020).

The integration of HSI and LIDAR offers enhanced assessment of canopy structure, biomass and soil properties, although limitations such as laser obscuration and incomplete trait retrieval highlight the need for sensor fusion approaches (Walter *et al*., 2019).UAV-based hyperspectral imaging has proven effective for measuring leaf area index (LAI) and soil moisture, while AI-driven analysis of UAV data further enables prediction of soil organic carbon and erosion patterns, supporting sustainable land management (Sishodia *et al*., 2020).

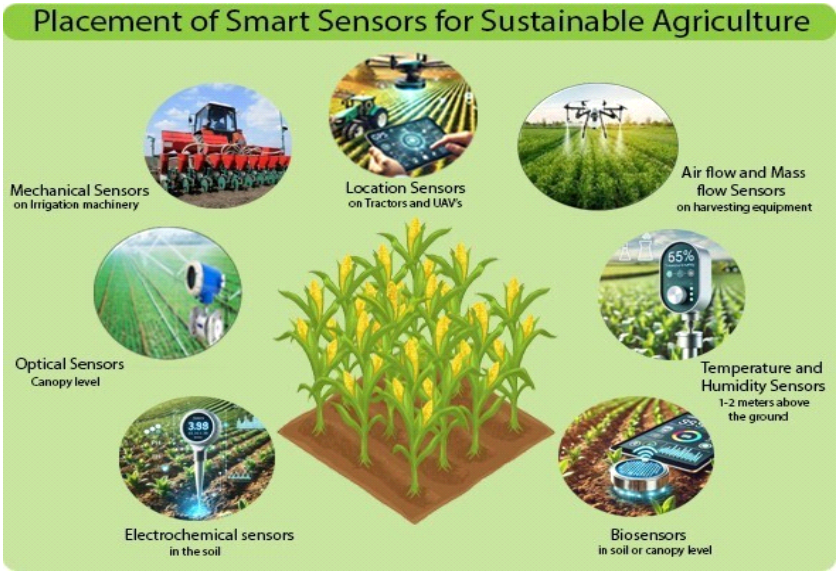
Elastic scattering forms the basis of biosensing, using broadband or solar illumination to detect spectral changes from photon interactions (Cavaco *et al*., 2022). Near-infrared spectroscopy (NIRS) rapidly and non-destructively evaluates soil attributes such as organic matter, minerals, pH and heavy metals (Leone *et al*., 2022), while fiber-optic and ceramic-based probes enhance volumetric water content measurement. Proximal sensors with fluorometers track chlorophyll fluorescence to detect stress or disease

(Sankaran *et al*., 2010). Multispectral and Hyperspectral Imaging (MSI and HSI) systems, employing silicon, CMOS, or InGaAs detectors with diffraction gratings and optical coatings, capture broad to continuous spectra (350-2500 nm) for plant and soil monitoring (Luo *et al*., 2022). Thermal imaging, based on vanadium oxide or amorphous silicon sensors, links leaf temperature with transpiration and water stress (Parihar *et al*., 2021). LiDAR, using laser diodes with avalanche photodiodes or silicon photomultipliers, measures canopy structure, biomass and gas concentrations such as CO_2 *via* DIAL and supports data fusion with HSI (Bietresato *et al*., 2016). Agricultural CO_2 sensors apply infrared absorption with optical materials like germanium or sapphire (Butt *et al*., 2025), while multispectral laser scanners integrate multiple wavelengths and MEMS-based optics for compact reflectance measurements (Takhtkeshha *et al*., 2024). Integrated platforms combining LiDAR, MSI, thermal sensors and GPS, often built with lightweight carbon fiber and polymers, enable sensor fusion to assess NDVI, LAI, fruit count, canopy traits and yield potential (Lu *et al*., 2020).

Biosensors

Biosensors are analytical devices that integrate a biological recognition element with a physicochemical transducer to detect specific analytes and they have found significant applications in agriculture for monitoring soil nutrients, detecting pathogens and assessing crop health. These sensors help enable real-time, *in-situ* diagnostics, contributing to precision farming practices. The core components of a typical nanobiosensor include a biologically sensitized probe (such as enzymes, antibodies, nucleic acids, or molecular imprints), a transducer that converts biological interactions into electrical signals and a detector that processes and displays the data (Rai *et al*., 2012).

Materials used in agricultural biosensors have evolved considerably. For instance, porous ceramic disks are employed in commercial sensors like TEROS 21, where dielectric ceramic elements form a capacitor whose charging time varies with soil water content (Farhad *et al*., 2023). Further advancements include the development of electromagnetic sensors using air-core inductive coils made from 0.6 mm enameled copper wire, designed to



Optical sensors are positioned on plants or integrated into Unmanned aerial vehicles (UAVs), they monitor plant health, light intensity and chlorophyll content to assess growth and health. Biosensors are embedded on plants or in the soil, detecting biological changes like pest infestations or pathogen presence for early intervention. Temperature and humidity sensors are placed in field corners or on irrigation systems, they track environmental conditions to optimize crop growth and prevent diseases. Mechanical sensors are installed on plants or soil or on irrigation machinery, they measure physical stress, root growth and plant deformation for better irrigation and harvesting strategies. Electrochemical sensors: Are positioned in the soil, they measure pH, nutrient levels and chemical presence for precise soil management. Air flow and mass flow sensors are positioned in ventilation and irrigation systems, they monitor air and mass flow to ensure optimal water and nutrient distribution. Location sensors are attached to tractors, UAVs, or fixed points in the field; they provide geospatial data for field mapping, yield estimation and site-specific crop management.

Fig 1: Schematic representation of placement of smart sensors on plants and in agricultural fields to support precision farming and sustainable agricultural practices.

detect changes in soil moisture by tracking variations in mutual inductance and resonance frequency based on water content and soil type (Lloret *et al*., 2021). Recent sensor systems also integrate innovative materials such as self-fabricated nanoceramic-based thermistors and indium tin oxide (ITO) nanopowder-based electric heaters (Hassan *et al*., 2023). These are assembled with stainless steel cylindrical probes, 3D-printed enclosures and NodeMCU microcontrollers for compact, efficient and field-deployable sensing solutions.

Temperature and humidity sensors

Temperature and humidity sensors play a critical role in precision agriculture by enabling real-time monitoring of microclimatic conditions such as leaf surface temperature and ambient humidity. These sensors help optimize irrigation schedules, detect plant stress and improve overall crop productivity. With the advancement of flexible electronics, the application of these sensors has significantly expanded, allowing for continuous, long-term attachment to plant surfaces to directly monitor physiological and environmental parameters (Ikram *et al*., 2024). Flexible temperature and humidity sensors are typically fabricated using a range of materials that enhance their sensitivity, accuracy and response time. The substrates used for these sensors include flexible polymers and inorganic nanomaterials, such as polyimide (PI), polydimethylsiloxane (PDMS), polyester (PE), polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) (Tai *et al*., 2020). For sensing layers, both inorganic and organic materials are employed. Resistive and capacitive polymeric materials are widely used for both temperature and humidity sensing due to their adaptable electrical properties (Jesus *et al*., 2023). In terms of sensing mechanisms, temperature sensors are categorized into thermosensitive, thermoresistive and thermoelectric types, while humidity sensors are generally classified as relative humidity (RH) sensors and absolute humidity (moisture) sensors (Ikram *et al*., 2024). For humidity sensing, most commercial devices are based on metal oxides, porous silicon and polymers that exhibit significant changes in electrical properties-such as resistivity and capacitance-upon adsorption of water vapor. Common oxide-based sensing materials include Al_2O_3, TiO_2, SiO_2 and spinel compounds, while wide-bandgap semiconductors like SnO_2, ZnO and In_2O_3 are frequently used due to their water-sensitive conductivity (Chen and Lu, 2005). Capacitive humidity sensors operate by detecting changes in the dielectric constant of the sensing material as relative humidity (RH) varies, whereas resistive-type sensors rely on changes in impedance or resistance, with water adsorption increasing conductivity in n-type ceramics. These sensors generally consume low power but require frequent calibration due to changes in permittivity. Additionally, carbon-based materials such as carbon nanotubes (CNTs), graphene, carbon nanofibers and carbon black are increasingly used due to their high surface area and tunable surface chemistry, which significantly enhance sensitivity (Tulliani *et al*., 2019).

Advanced composites that integrate carbon nanomaterials with polymers, ceramics and semiconductors have been developed to further improve sensing performance. Materials like graphene oxide (GO), CNTs and various nanocoils have been explored for their potential in fabricating high-performance, flexible humidity sensors (Tai *et al*., 2020). These innovations in material design and sensor architecture mark a substantial step forward in environmental monitoring tools for smart farming.

Mechanical sensors

Mechanical sensors are essential tools in modern agriculture for evaluating physical properties of both soil and plants. These sensors can measure parameters such as soil compactness, mechanical resistance, plant elongation, sap flow and stem circumference. Such data is invaluable for optimizing irrigation, monitoring plant growth and understanding soil-plant interactions. Devices like the Honeywell FSG15N1A measure the force exerted by plant roots to absorb water, providing insights into plant health and soil conditions. The foundation of advanced mechanical sensor design lies in the materials used. Early strategies focused on standard semiconductors like silicon, silicon carbide and gallium nitride and metals such as gold (Au), platinum (Pt) and aluminum (Al). These materials were engineered into nanomembranes with low bending stiffness and transferred onto soft polymers via mechanical stamping for flexibility (Nguyen *et al*., 2022). Another approach utilizes intrinsically stretchable conductive polymers such as PEDOT:PSS, which form the basis of soft, functional electronic components (Yang *et al*., 2020).

Mechanical sensors have evolved to include strain sensors capable of detecting plant elongation and movement. Gallium-based liquid alloys (LA) printed on water-soluble polyvinyl alcohol (PVA) films created flexible, morphing circuits capable of dynamic plant monitoring (Jiang *et al*., 2020). Gold nanofilms on micro-thick PDMS substrates increased stretchability by up to 35%, while serpentine copper interconnects pushed it further-up to 150% in one direction and 60% in another (Zhao *et al*., 2019).

Three-dimensional structures have also been introduced to improve flexibility and minimize impact on plants. Zhang *et al*. (2024) demonstrated a sensor fabricated by laser-thinning a 100 µm polyimide (PI) film into crease-like arch structures, allowing for 100% strain detection while maintaining minimal surface contact, thus avoiding plant stress (Zhang *et al*., 2024). Similarly, a scorpion-inspired sensor used nanometer-thick silver films on polyethylene glycol terephthalate (PGT) to detect subtle changes in plant circumference, as observed in a lucky bamboo plant (Huang *et al*., 2023). A recent study employed a low-cost piezoelectric, non-contact mechanical ultrasonic sensor integrated with a LabVIEW-based system to measure and classify potatoes of different sizes, demonstrating the efficiency and affordability of the method (Beyaz and Gerdan, 2020).

Another breakthrough has been in microneedle-based sensors. These miniature thermal probes, made from silicon wafers or flexible printed circuit boards (PCBs), are used to measure sap flow in stems through hot-wire anemometry (Kim and Lee, 2024). The PCB alternative offers mechanical flexibility and reduced brittleness compared to silicon. Additionally, integrating electrodes on microneedles enables multimodal sensing, such as detecting glucose and pH in plant sap (Chen *et al*., 2024; Ece *et al*., 2023). However, despite their miniaturization, microneedles still pose a risk of damaging xylem tissue.

In summary, the integration of advanced materials-ranging from traditional metals and semiconductors to conductive polymers, nanomaterials and 3D-printed structures-has driven rapid progress in mechanical sensor technologies.

Electrochemical sensors

Electrochemical sensors have emerged as powerful tools in agricultural monitoring, offering real-time, sensitive and cost-effective detection of various chemical and biological markers. These sensors convert chemical information-such as the concentration of specific ions, plant hormones, or pesticide residues-into an electrical signal, enabling precise and rapid monitoring of plant health, nutrient levels, environmental stressors and contaminant presence. They are particularly suitable for precision agriculture (PA) due to their high selectivity, portability and ability to operate in complex matrices with minimal sample preparation.

Electrochemical sensors are largely categorized by the types of materials used for their construction, particularly in the working electrode and ion-selective membranes. One widely used configuration is the ion-selective electrode (ISE), which incorporates a polymer membrane doped with ionophores-chemical compounds that selectively bind target ions. These membranes exhibit excellent processability and are effective in detecting various analytes (Chen *et al*., 2018). Solid-contact ISEs (SC-ISEs) sensors utilize materials such as reduced graphene oxide aerogel (rGOA) as the ion-to-electron converter, enhancing signal stability (Kim *et al*., 2021). Screen-printed electrodes (SPEs) have also gained popularity due to their low cost, reproducibility and ease of fabrication. An SPE-based nitrate sensor with a copper reference electrode effectively monitored soil inorganic nitrogen (Artigas *et al*., 2003), while laser-induced graphene electrodes in SC-ISEs enabled simple, low-toxicity detection of NO_3^- and NH_4^+ in soil slurry (Zhang *et al*., 2022). Electrochemical sensors have also been adapted for the real-time detection of plant hormones, which serve as indicators of physiological and stress responses. For example, a stainless steel (SS) wire-based microsensor was developed to detect 3-indole acetic acid (IAA), a key auxin, with a detection limit as low as 43 pg/mL under saline stress in soybean stems (Li *et al*., 2019). Similarly, disposable electrodes modified with multi-walled carbon nanotubes and Nafion were used to detect salicylic acid (SA)-a stress-signaling hormone released during infection. The enhanced sensitivity of this sensor enabled differentiation between healthy and Botrytis cinerea-infected tomato leaves (Sun *et al*., 2020). Methyl jasmonate (MeJA) was successfully detected using a nano-montmorillonite/glassy carbon electrode (nano-MMT/GCE) (Gan *et al*., 2010), while ethylene was selectively identified using a SWCNT network modified with a fluorinated copper(I) complex, providing a unique mechanism based on resistance changes due to ligand binding (Esser *et al*., 2012).

More advanced biosensors, such as organic electrochemical transistors (OECTs), offer amplified signals and tight biological integration. An OECT-based sensor cross-linked with glucose oxidase and chitosan has been used to monitor glucose production in chloroplasts at different metabolic stages (Naikoo *et al*., 2021). Other devices have tracked biomarker expression like β-glucuronidase (GUS) in transgenic tobacco cells using microchip-based chronoamperometry (Pandey *et al*., 2018).

LIG-based flexible electrodes have also been utilized to detect organophosphorus pesticides, such as methyl parathion, by functionalizing them with organophosphorus hydrolase (OPH). These systems can interface with smartphones for real-time data transmission (Zhao *et al*., 2020). Innovations like 3D-printed plant copters and humidity sensors using GO-decorated LIG electrodes further demonstrate the versatility of wearable systems (Li *et al*., 2018).

Electrochemical methods are particularly suitable for detecting pesticide residues. Metal-based electrodes-such as those made from silver, gold and mercury-have long been effective for detecting herbicides like paraquat (PQ) due to their high electrooxidation capacity (Souza and Machado, 2005). Recent work has also explored metallic nanoparticles (*e.g*., Pt, Pd, Cu) to enhance surface area and catalytic activity. Electrodes incorporating multi-walled carbon nanotubes and nickel hydroxide nanoparticles have been shown to improve PQ detection in fruits like apples and oranges (Jin, 2012). Additionally, DNA-modified gold nanoparticles immobilized on electrodes allow for highly sensitive PQ detection *via* electrochemical signal amplification (Ribeiro *et al*., 2010).

Airflow and mass flow sensors

Airflow and mass flow sensors play a vital role in precision agriculture by enabling real-time monitoring and control of material movement during critical farming operations such as sowing, harvesting and cleaning. These sensors are essential for improving operational efficiency, minimizing losses and ensuring the accurate application of inputs. In grain cleaning systems, for example, airflow sensors help optimize the separation of grains from chaff and debris, while mass flow sensors assist in measuring the rate at which seeds or harvested grains are transported, thus ensuring uniformity and precision in crop management.

Recent advances in sensor design have led to the development of more accurate and robust sensing mechanisms. One such system integrates a near-infrared laser emitter (Shenzhen Fulei Technology Co., Ltd.,

Shenzhen, China) with a silicon photocell (Shanghai Xu'erhong Electronic Technology Co., Ltd., Shanghai, China), both aligned on a common axis to detect grain flow and density changes with high precision (Zhang *et al*., 2024).

Additionally, indoor apparatuses simulating the sowing process using grain drills have been developed. These setups typically incorporate a fluted roller rotated by a motor at different speeds (2, 4 and 6 rpm) to mimic various seed mass flow rates (Al-Mallahi and Kataoka, 2013). Such systems enable accurate modeling and calibration of mass flow sensors for real-field conditions. Capacitance sensors are another commonly used technology for determining physical properties of plant materials, especially moisture content. These sensors operate on the principle that the dielectric constant of a material-air mixture increases with the density of the material between parallel plates. Capacitance measurements can thus infer material characteristics such as moisture. Multiple frequency parallel plate capacitors have been successfully used to determine the moisture content in hay and forages (Lawrence *et al*., 2001).

Millimeter-wave FMCW radar has recently been applied to measure peanut mass flow rate for yield monitoring. A radar-based sensor, mounted outside a plastic duct in the pneumatic conveyor of a peanut combine, was tested on both research- (2-row) and commercial-scale (6-row) setups (Bidese-Puhl *et al*., 2023). The system generated time-series range and velocity data correlated with mass flow rates, providing reliable measurements along with useful feedback such as peanut velocity for optimizing conveyor air pressure.

Location sensors

Location sensors are essential in agriculture for applications such as environmental monitoring, precision farming, machine control, facility automation and traceability systems (Wang *et al*., 2006). They enable accurate spatial data collection, helping farmers map fields, monitor crop conditions and optimize resource use.

Technologies like geographic information systems (GIS) and global positioning systems (GPS) allow multi-layered mapping and analysis of attributes such as yield, soil properties, pest infestations and water availability. GIS enhances decision-making through geospatial analysis, while GPS provides precise location data for activities like site-specific input application, improving productivity and reducing costs. Remote sensing (RS), combined with GIS and GPS, supports critical agricultural tasks such as crop health monitoring, soil moisture estimation, stress detection and yield forecasting.

Advancements in sensor materials, including flexible polymers, organic semiconductors and nano-engineered components, have led to more lightweight, durable and highly sensitive location sensors. Modern innovations like real-time kinematic (RTK) GPS and sensor fusion techniques further improve data accuracy and resilience (Hossain *et al*., 2024).

The integration of GIS, GPS and RS technologies enables efficient land use planning, crop monitoring and yield prediction, providing critical spatial intelligence for precision agriculture. These technologies offer rapid, cost-effective and real-time data solutions, essential for sustainable agricultural productivity (Bajaj *et al*., 2023).

To better understand the integration of smart sensing technologies in agriculture, Table 1 summarizes various types of sensors deployed in agricultural fields along with the materials used in their construction.

Research gap and critical insights

Despite considerable advances in precision agriculture, significant gaps remain in aligning sensor-material innovations with the functional and environmental demands of agricultural systems. In evaluating materials for agricultural sensor applications, five core performance metrics emerge: Sensitivity, response/recovery time, stability (including drift), durability under field conditions and cost-scalability. High sensitivity and rapid response enable real-time detection of subtle physiological or environmental changes; stability ensures consistent performance under fluctuating temperature, humidity and soil conditions; durability defines the operational lifetime in harsh outdoor environments; and cost-scalability determines feasibility for large-scale deployment. Together, these parameters define the overall efficiency, reliability and practicality of sensor materials in precision agriculture systems.

Optical sensors, particularly those based on plasmonic and photonic principles, have benefited from graphene-enhanced surface-plasmon-resonance (SPR) layers, which improve refractive-index sensitivity and detection resolution. (Tene *et al*., 2024) However, the environmental stability and anti-fouling capability of such coatings under dusty, humid field-conditions remain insufficiently characterised. In biosensors, nanostructured materials such as graphene, MXenes and carbon nanotube-polymer hybrids have enabled ultrasensitive detection of agrochemicals and pathogens (for example, MXene-nucleic acid biosensors in food/agriculture) (Wang and Gunasekaran, 2022). Yet signal drift, surface degradation and limited field validation on leaf or soil matrices restrict practical adoption. For temperature and humidity sensors, flexible polymer composites and MOF-polymer hybrids are emerging for plant and soil monitoring; however, sensor ageing and hysteresis under cyclic climatic fluctuations remain unresolved (Pasalwad *et al*., 2025). Mechanical sensors employing PVDF-based piezoelectric polymers effectively quantify plant growth dynamics and soil compaction, but suffer from mechanical abrasion and bio-fouling-necessitating protective hybrid encapsulants (Ahbab *et al*., 2025). In electrochemical sensors, graphene-metal oxide nanohybrids enhance electron-transfer and detection sensitivity for nutrient and contaminant assays; still, electrode fouling and calibration instability under variable soil electrolytes persist as major challenges (Ahbab *et al*., 2025; Immanuel *et al*., 2019). Similarly, airflow

Table 1: Overview of sensor types and materials utilized in agricultural applications.

Types of sensors	Materials used for making the sensors	References
Optical sensors	Tungsten filaments, arc lamps; optical fiber probes and nanoporous ceramic disks photodetectors diffraction gratings and high-resolution spectrometers; narrow-bandpass filters, CMOS; laser diodes; 3D point clouds optical materials;multi-layer dielectric mirrors, temperature-stable laser crystals and scanning MEMS components;carbon fiber and high-strength polymers.	(Cavaco *et al*., 2022), (Luo *et al*., 2022), (Butt *et al*., 2025), (Takhtkeshha *et al*., 2024)
	Biologically sensitized probe, Transducer, detector, porous ceramic disks;dielectric ceramic elements, Ion-sensitive field-effect transistors (ISFETs); Nanoceramic-based thermistors and indium tin oxide (ITO) Nanopowder-based electric heaters.	(Leone *et al*., 2022), (Hassan *et al*., 2023)
Temperature and humidity sensors	Flexible polymers and inorganic nanomaterials, Resistive and capacitive polymeric materials; metal oxides, porous silicon and polymers; semiconductors; carbon-based materials; carbon nanomaterials; graphene oxide (GO), CNTs and nanocoils.	(de Jesus *et al*., 2023), (Tai *et al*., 2020)
Mechanical sensors	Standard semiconductors and metals; stretchable conductive polymers; fiber Bragg gratings (FBGs); polyaniline (PANI) nanoparticles;Gallium-based liquid alloys (LA); Gold nanofilms,copper; laser-induced graphene (LIG); thermal probes,integrating electrodes.	(Nguyen *et al*., 2022), (Zhang *et al*., 2024), (Kim and Lee, 2024), (Chen *et al*., 2024)
Electrochemical sensors	Ion-selective electrode (ISE);polymers; reduced graphene oxide aerogel (rGOA); Screen-printed electrodes (SPEs);laser-induced graphene (LIG); carbon nanotubes and Nafion; glassy carbon electrode (GCE);organic electrochemical transistors (OECTs); Metal-based electrodes;metallic nanoparticles; DNA-modified gold nanoparticles.	(Kim *et al*., 2021), (Zhang *et al*., 2022), (Sun *et al*., 2020), (Naikoo *et al*., 2021)
Airflow and mass Flow sensors	Vibration feeder, a fan, a vibrating screen and screw conveyors; laser emitter; silicon photocell; multiple frequency parallel plate capacitors	(Zhang *et al*., 2024), (Lawrence *et al*., 2001).
Location sensors	Polymers, organic semiconductors and nano-engineered components	(Hossain *et al*., 2024)

and mass flow sensors utilising CMOS-MEMS thin-film heaters require robust encapsulation for dusty environments, while location and IoT based sensors demand durable, conductive and flexible antenna materials capable of long-term outdoor deployment (Yang *et al*., 2025).

Collectively, these observations reveal a persistent research gap in translating laboratory-scale material innovations into field-ready agricultural sensors. Despite extensive progress in nanomaterial synthesis and sensor miniaturization, there remains insufficient integration between material functionality and agro-environmental performance requirements. A lack of systematic studies addressing long-term durability, environmental stability and standardised benchmarking under real field conditions limits the scalability of current prototypes. Therefore, future research must focus on materials-application co-design, hybrid composite optimization and the establishment of uniform performance evaluation frameworks to bridge the gap between high-performance laboratory materials and reliable, sustainable agricultural sensing platforms.

CONCLUSION

This manuscript provides a comprehensive overview of the materials and technological innovations utilized in the development of various agricultural sensors. The integration of flexible substrates, nanomaterials and functional coatings has enabled the creation of highly sensitive, multifunctional and field-deployable sensors, offering significant advantages for precision agriculture. However, challenges such as material degradation under harsh environmental conditions, calibration complexities and the high initial costs of advanced sensors still limit widespread adoption. Addressing these limitations through material innovation and system integration will be critical

for the broader adoption of sensor-based technologies in precision agriculture. Future research should focus on improving sensor durability, reducing costs and enhancing multi-parameter integration to fully realize the potential of smart agricultural monitoring systems.

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Conflict of interest

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