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SENSOR-BASED PLANT AND SOIL HEALTH MANAGEMENT

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ABSTRACT

Precision agriculture is advancing toward sustainable, need-based plant management using sensors, which offer real-time data on environmental and physical conditions. These sensors, classified as analog or digital (by output) and active or passive (by energy source), are widely applied in soil health, irrigation, nutrient management, pest control, yield forecasting, and toxin detection. Common types include optical, electrochemical, and nano-sensors like carbon nanotubes and quantum dots, valued for their high accuracy and efficiency. Sensors ultimately enhance precision, reduce environmental impact, and are pivotal in modernizing smart plant management.

KEYWORDS: Sensors, Biosensors, Nano-sensors, Precision Agriculture, Soil health.

INTRODUCTION

With the advent of Green Revolution technologies, there has been an imbalance observed in the inputs application which has ultimately resulted in an unstable agricultural system. This has paved the way for precision agriculture which relies on the principle of 'need-based input application'. Sensors play an important role in precision farming, especially in the monitoring part. This leads to a sensing gradient in agricultural systems and the application of inputs by the requirements. Hence, sensors can be used in monitoring properties of soil and plant domains and management steps thus taken can optimize system output and minimise loss. Moreover, sensors such as optical, electrochemical, bio-sensors and nano-sensors can be used at the farm level as well as large scale to study systems on a wider basis and mapping of resources. This paper mainly focuses on different types of sensors used in agriculture and their role in soil health, irrigation, nutrient management and mapping.

SENSOR AND ITS TYPES

'A sensor is a device, module, machine, or subsystem that detects events or changes in its environment and relays the information to other electronics, most commonly a computer processor. A sensor converts physical phenomena into a measurable digital signal, which can then be displayed, read, or processed further.' (Javaid *et al.*, 2021) It detects input such as heat, light, moisture, motion, pressure or any other phenomena and responds to it.

Sensors are of different types based on their working mechanisms. Based on energy sources there are two types of sensors: active and passive sensors. While active sensors produce or emit their own energy, passive sensors rely on naturally existing external energy like solar energy or radiation. Therefore, active sensors have more flexibility in terms of the time of usage as they can be used at any time of the day and night while the use of passive sensors is more restricted in terms of timing and occasionally weather conditions. Based on output type, sensors are of two types: Analog and Digital. Analog sensors result in continuous and varying output and are used more in pressure and temperature monitoring, sound detection, acceleration measurement, etc. while on the other hand, discrete signals in a binary format are transmitted in digital sensors which are used in measuring conductivity, pH, dissolved oxygen, ammonia and nitrate concentration.

USE OF SENSORS IN AGRICULTURE

- *Soil Health Management:* Soil sensors aid in monitoring pH, moisture, temperature and nutrient levels. This can provide a deeper insight into soil health over time as affected by agronomical practices which also helps in improvising farm management prioritizing soil health along with yield. Moreover, sensors give real-time monitoring thus preventing the overuse of inputs.
- *Species Identification:* Multispectral and Hyperspectral sensors capture images and data beyond the visible range of the spectrum and aid in species identification. They can thus differentiate between crops and weed species. Moreover, they also help in the identification of crop species with specific traits and their growth patterns. Sensors mounted on drones also assess biodiversity over a large area.
- *Irrigation and Nutrient Management:* Sensors monitoring soil moisture content and tension can be used in scheduling irrigation time as well as amount thus avoiding under or over-watering. This can result in yield optimization and water conservation. Moreover, micro-irrigation systems like drip and sprinkler can be paired with moisture sensors which on base of real-time data can provide automatic water supply thus providing optimal plant growth conditions. Nutrient sensors help in the detection of nutrients like nitrogen, phosphorus and potassium in the soil along with the gradient or heterogeneity present in the soil in terms of specific nutrients. This enables farmers to apply fertilizers more efficiently using variable rate technology (VRT) thus correcting deficiency and avoiding toxicity. pH sensors along with assisting in the maintenance of optimal required crop-

specific pH, give an insight into possible nutrient toxicity or management practice loopholes and microbial diversity of soil.

- *Soil Mapping:* Soil maps can be made on farm, regional, state or national level based on soil properties like texture, colour, organic matter, nutrient and moisture content or pH using sensors thus guiding in the management of irrigation, fertilization and inputs based on variation in soil properties. Electromagnetic induction (EMI) and Ground Penetrating Radar (GPR) are used to map soil texture and organic matter content.
- *Pest Identification and Assessment:* Sensor-based pest management enables early detection and precise targeting of pest infestation. Optical sensors and imaging systems capture and monitor pest activity. Thermal sensors are useful in detecting the kind and extent of stress and damage caused by pathogens. Moreover, automated sensor-based traps detect specific pests and provide an alert for timely interventions.
- *Yield Forecasting:* Integrating thermal imaging, multi and hyper-spectral sensors provide data on different plant growth stages, biomass and crop health which are indicators of potential yield aid in yield forecasting. Moreover, 3D models of crop canopies can be created using LiDAR (Light Detection and Ranging) sensors that aid in estimating yield volume by providing data to machine models.
- *Detection of Toxins and Pesticide Residues:* Sensors detecting pesticide residues and other toxic residues enhance the safety of agricultural products. Harmful chemicals can be detected on crops and soil using biosensors and nanosensors ensuring compliance with standards of food safety. Furthermore, heavy metals, pesticides and other toxins can be tracked in soil, crops and food products.

Table 1. Types of sensors used in agriculture

Sensor	Particulars	Applications	Limitations
Optical Sensors	Detection of light intensity and wavelength variations. Measuring absorption and reflectance of light in visible,	**Plant Health Monitoring**: Detection of chlorophyll content, which indicates photosynthetic activity, plant vigour, water content and nutrient status. **Disease Detection**: Early detection of pest infestation and diseases by	**Calibration Sensitivity:** requires more frequent calibration. **Environmental Interference**: Cloud cover, fog, dust and varying light conditions

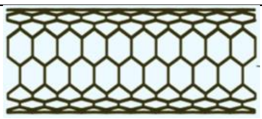
	near-infrared (NIR), and ultraviolet (UV) spectra.	sensing abnormal spectral reflectance patterns. **Soil and Water Management**: The use of multispectral or hyperspectral imaging in monitoring soil moisture, nutrient levels and salinity can be, help in optimizing irrigation and fertilization.	can affect the measurement quality.
Plant Wearable Biosensors	Allow real-time monitoring of plant physiological processes. They conform to the plant's surface as they are based on flexible electronics and measure water, gases and nutrient movements and levels in plants.	**Nutrient Deficiency Monitoring**: Nutrient levels (like nitrogen or phosphorus) can be detected within plant tissues to facilitate timely fertilizer application. **Water Stress Sensing**: Irrigation can be scheduled by water level sensing by monitoring stomatal conductance or sap flow. **Environmental Monitoring**: Tracking of temperature, humidity, toxins and volatile organic compounds (VOCs) around the plant.	**Durability** **Power Supply**: Creating self-sustaining power systems for continuous monitoring and data collection is a challenge.
Electro-chemical Sensors	The chemical changes at the surface of the sensor are converted into electrical signals.	**Soil Nutrient Sensing**: by ion detection. **pH and Salinity Monitoring** **Biotic and Abiotic Stress Detection**: Detection of chemicals such as hydrogen peroxide, ethylene or nitric oxide released during plant stress events.	**Sensor Fouling**: Biofouling or chemical degradation of the sensor's surface. **Integration and Scalability**: Large-scale implementation while maintaining accuracy and

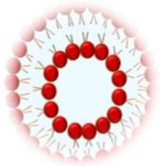
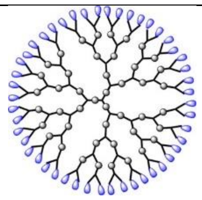
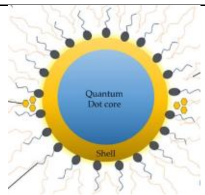
		Detect the occurrence of metabolic diseases in animals (Kundu *et al.,* 2019)	minimizing costs is difficult.
Heavy Metal Sensors	Detection of toxic metals like lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg).	**Soil Contamination Monitoring:** Detection of heavy metal present and monitoring of levels. **Water Quality Control:** Heavy metals are present in irrigation water. **Food Safety**: Assessment of metal concentrations in plant tissues to ensure that harvested crops meet safety standards.	**Sensitivity**: Achieving low detection of specific ions can be difficult. s **Long-Term Monitoring**: Maintenance of high performance and resistance to degradation over time, especially in harsh agricultural environments.

NANO-SENSORS IN AGRICULTURE

The use of nanosensors in agriculture has been increasing mainly due to their high sensitivity and accuracy owing to their small size and sustainability thus making them more versatile across various dimensions. Nano-sensors are often made up of metals (e.g., gold, silver, platinum) or metal oxides (e.g., zinc oxide, titanium dioxide), carbon nanotubes, graphene, quantum dots, dendrimers, piezoelectric materials, liposomes and biorecognition elements (enzymes, antibodies, or nucleic acids). Each type of nanosensor can be customized depending on the specific application in agriculture, enabling real-time, site-specific monitoring for efficient and sustainable farming.

Table 2. Types of Nano-sensors and their use in Agriculture (Bharti *et al.,* 2024).

Types of sensors	**Image**	**Particulars**	**Use in Agriculture**
Carbon nanotubes		Can easily penetrate plant cell walls.	Influence regulation of plant growth, Medium for biosensors Agricultural smart delivery

Fullerene		strong adsorption of organic molecules due to large specific surface area, good biocompatibility, inert behaviour, stable structure, and high electronic conductivity	Enhancement in water retention by plants thus increasing biomass and fruit yield.
Liposomes			tracking and monitoring very low concentrations of organophosphorus pesticides
Dendrimers		Highly branched, tree-like structure	Controlled Release of Fertilizers and Pesticides Delivery of Genetic Material Encapsulation and Protection of Beneficial Microbes
Optical nano-sensors		Forster resonance energy transfer (FRET) principle	Studying protein-protein interactions, cell contents and biophysical parameters
Quantum Dot Nano-sensor		Use of fluorescence principle	Pathogens detection
Electrochemical biosensors		Change in electrochemical properties of sensors based on change in parameters to be measured	pH, moisture content, temperature, nutrient levels
Enzyme-based Biosensor		Works on principle of change in enzymatic	Monitoring nutrients, pollutants, enzymes

		activity with change in nutrient dynamics and pollutants presence	

CONCLUSION

The use of sensors in agriculture is pivotal for transitioning from conventional generalized farming to precision farming, where inputs are applied based on real-time needs. Various types of sensors, including optical, electrochemical, biosensors and nanosensors, provide invaluable data on soil health, species identification, irrigation, nutrient management, soil mapping, yield forecasting and pest detection. The use of nanosensors further enhances sensitivity and accuracy in monitoring and managing agricultural systems. This sensor-based approach not only optimizes productivity but also minimizes adverse environmental impact building a base for more sustainable and efficient farming practices.

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