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THE CURRENT STATE OF INTEGRATION OF IOT TECHNOLOGIES IN AGRICULTURAL MACHINERY AND EQUIPMENT

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Abstract: Recent years have seen a substantial acceleration of the digitalization of agriculture, with Internet of Things (IoT) technologies playing a pivotal role in this change. Real-time operational parameter monitoring, resource consumption optimization, and increased operational efficiency are made possible by the integration of sensors, communication systems, and data analytics platforms into agricultural equipment and installations. At the moment, IoT technologies help advance predictive maintenance, process automation, and precision agriculture, which lowers costs and improves the sustainability of farming operations. The purpose of this review paper is to examine the current state of IoT technology integration in agricultural equipment and installations, emphasizing the primary uses, advantages, and related difficulties.

Keywords: precision agriculture, smart farming, sustainable agriculture, digital agriculture

INTRODUCTION

In the context of agriculture, the Internet of Things (IoT) refers to networks of interconnected sensors, actuators, and cloud-based platforms that make it possible to automate and monitor vital agricultural processes in real time. To support data-driven decision-making, these systems gather extensive, high-resolution data on crop growth, pest infestations, soil characteristics, and climate. By using machine learning (ML) and deep learning (DL) algorithms to evaluate sensor data, forecast future events, and automate reactions, artificial intelligence (AI) further improves these capabilities and reduces the need for human intervention [1].

The concepts of Agriculture 4.0 and Agriculture 5.0 are frequently used to frame the development of precision agriculture [2]. Known as the "Digital Revolution in Agriculture," Agriculture 4.0 places a strong emphasis on utilizing advanced technologies to support productive farming methods. Precision agriculture is greatly improved by Agriculture 4.0 thanks to a number of technical developments that increase farming methods sustainability, accuracy, and efficiency. Farmers can make well-informed decisions by using IoT sensors to gather real-time data on variables like crop health, temperature, and soil moisture. Big data analytics also aids in trend identification and predictive evaluations that maximize the use of available resources [3].

High-resolution imaging is provided by drones fitted with multispectral sensors, allowing for remote field monitoring and the identification of problem regions. By evaluating data to forecast results and automate irrigation, fertilization, and pest management decision-making processes, artificial intelligence (AI) and machine learning (ML) further support precision agriculture [4,5].

The foundation of precision farming is the integration of modern innovations in the fields of artificial intelligence (AI) and the Internet of Things (IoT) to enable autonomous farming practices. In order to enhance agricultural processes, these systems integrate sensors, software platforms, and equipment to establish a digital infrastructure that can gather, transmit, process, and analyze data in real time [6].

MATERIALS AND METHODS

The technological architecture of IoT for agricultural applications

1. The main objective of the data collection layer (also known as the sensor/information collection layer) is to automatically and instantly transform physical data from actual agricultural output into digital information that can be analyzed in the virtual environment using a variety of methods. The Internet of Things for agriculture gathers data in the following categories:

- data from agricultural sensors, such as vital parameters, temperature, humidity, pressure, and gas concentrations;
- details regarding the brand, model, attributes, cost, and other details of agricultural items;
- data regarding the state of agricultural equipment operation, including device and equipment operating parameters;
- location details: product placement, etc. and positioning of agricultural resources.

2. Transport/Network Layer: This layer's the main responsibility is for collecting and consolidate agricultural data obtained from the sensor layer for processing. The transport layer, which manages data processing and transmission, is the brain and nerve center of the Internet of Things for agriculture. The integration of the Internet with

the telecommunications network, information center, network management center, and intelligent processing center are all included in the network layer.

3. Application Layer: This layer's primary responsibility is to interpret and evaluate the data generated in order to provide a digital representation of the physical world. It combines agricultural market knowledge with the Internet of Things [7].

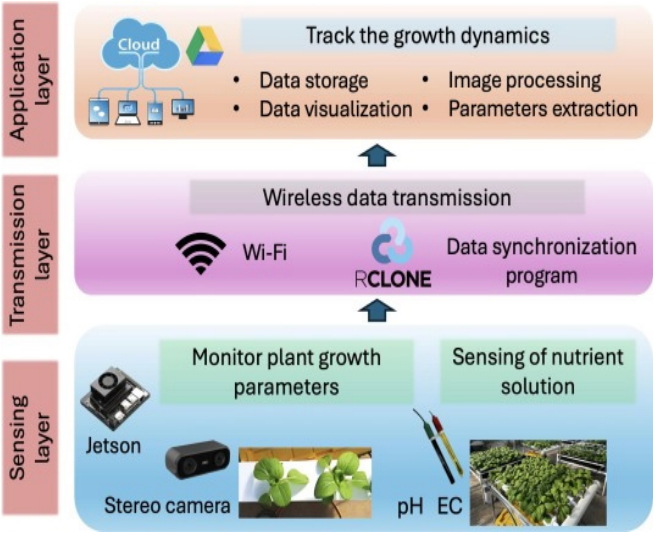

Figure 1. The IoT architecture of the vegetable growth monitoring system [8]

COLLETING DATA

Sensors are vital components of this technological ecosystem that monitor the agricultural environment's physical, chemical, and biological characteristics. These include:

- **Soil moisture sensors:** Because it influences microbial activity, water and nutrient availability, and plant growth, soil moisture is critical for soil health.

Farmers can determine when and how much to irrigate by using soil moisture sensors, which detect the amount of water in the soil. By avoiding both excessive and insufficient irrigation, this improves crop output and water efficiency. There are various sensor technologies, such as resistive and capacitive sensors. Capacitive sensors are energy-efficient and suitable for wireless monitoring; they measure changes in soil dielectric characteristics to detect moisture. The composition of the soil can affect resistive sensors, which detect electrical resistance. Water application is optimized through precision irrigation systems using sensor data and real-time analytics. Farming becomes more efficient by combining sensor data with automated irrigation, which maintains optimal growing conditions while saving water [5], [9], [10].

Mathematical model

$$C = \frac{\varepsilon A}{d} \qquad (1)$$

where: C is the electrical capacitance; ε - permittivity of the medium; A - surface area of the plates; d - distance between the plates

- **pH sensors:** Plant growth is influenced by soil pH because it affects microbial activity and nutrient availability.

Real-time monitoring made possible by precision agriculture aids farmers in managing their soil and fertilizing crops as efficiently as possible. Neutral to slightly acidic environments are ideal for microbial populations that facilitate nutrient cycling. Excessive pH levels can inhibit plant uptake and decrease nutrient solubility, which reduces productivity. Liming is crucial for long-term soil health since excessive acidity from excessive nitrogen consumption can harm soil structure. In order to provide information for well-informed agricultural decisions, modern pH sensors analyze soil conditions using electrochemical techniques. Although they provide real-time measurements, conductometric and potentiometric sensors need to be calibrated for accuracy. Crop yield and resource efficiency are increased while environmental impact is decreased when sensor technology is integrated with sustainable soil management. This approach supports sustainable agriculture and better use of natural resources [5,11,12].

Mathematical model - The Nernst equation:

$$E = E_0 + \frac{RT}{nF}\ln(a) \qquad (2)$$

where:

E - the measured electric potential (electrode voltage), expressed in volts (V). This is the value indicated by the sensor.

E_0 - standard electrode potential, expressed in volts (V). This is a constant specific to the electrochemical system, measured under standard conditions.

R - universal gas constant: R = 8.314 J/(mol·K)

T - absolute temperature, expressed in Kelvin (K). T(K) = T(°C) + 273.15

n - number of electrons transferred in the electrochemical reaction (for the pH electrode, usually n = 1).

F - Faraday constant: F = 96485 C/mol - electric charge of one mole of electrons

ln(a) - natural logarithm of ion activity:

a - ion activity (approximately equal to concentration in dilute solutions)

- **Temperature sensors:** Because it influences seed germination, plant growth, and decomposition processes, soil temperature—which generally ranges from -10 to 50 °C—is crucial for agriculture.

Additionally, it impacts soil microbial and chemical activity, which are essential for soil health and nutrient availability. A number of variables, including soil composition, moisture content, and thermal conductivity, influence temperature. Temperature changes are detected by soil temperature sensors, which then translate the data into digital form for study. Commonly used devices include thermistors, RTDs, and thermocouples. Rapid thermocouples are suitable for automated monitoring, and RTDs offer great precision. Although thermistors have good sensitivity, their nonlinear response requires calibration. By offering trustworthy information on soil conditions and heat dynamics, accurate temperature monitoring enhances agricultural practices and advances environmental knowledge. This supports better decision-making in crop management and resource use [5,13,14,15].

Mathematical model

$$R(T) = R_0(1+\alpha\,(T-T_0)) \qquad (3)$$

where: R(T) is the temperature resistance; R_0 - reference temperature resistance; α - temperature coefficient; T_0 - reference temperature

- **Nutrient sensors:** In precision agriculture, soil nutrient sensors—a cutting-edge technological development—are essential instruments for recognizing and quantifying important macronutrients including potassium, phosphorus, and nitrogen.

These sensors employ a range of detecting strategies, such as spectroscopic analysis, optical and electrochemical approaches, and ion-selective electrodes. Farmers may apply fertilizers more accurately with the use of real-time nutrient monitoring, increasing crop output and nutrient efficiency while lowering environmental effects such nutrient leaching. Nutrient assessment is possible in both lab and outdoor settings because to technologies includes Vis-NIR and ISFET sensors. Combining these techniques improves the sustainability and performance of managing soil fertility. Optimized nutrient application promotes ecologically friendly agricultural practices, lowers production costs, and uses less chemicals. This method promotes long-term agricultural sustainability and improves soil health [5,16].

- **Soil pollution sensors:** By recognizing and evaluating dangerous substances as heavy metals, pesticides, herbicides, and industrial chemicals, soil pollutant sensors are essential to contemporary agriculture and environmental management.

Excessive use of agrochemicals, industrial pollutants, and inappropriate waste disposal frequently exacerbate soil deterioration, affecting human health, ecological stability, and crop safety. Accurate and real-time pollutant monitoring is made possible by advanced sensing technologies. Biosensors use biological components like enzymes or microbes to specifically detect toxic substances, optical sensors use light-matter interactions to identify pollutants, and electrochemical sensors analyze changes in the electrical characteristics of soil linked to certain contaminants. Environmental monitoring, remedial techniques, precision fertilization, and soil health evaluation all make extensive use of these sensors. Soil pollutant sensors reduce hazards to the environment, preserve food quality, and promote sustainable agriculture management techniques by enabling early contamination detection [5], [17].

- **Insect/pest sensors**: By inducing injury to roots, bulbs, and aerial plant organs through feeding activities, plant diseases and pests drastically lower agricultural yield.

Insects that live in the soil, including flies, moths, butterflies, and beetles, are a major cause of crop losses. Advanced sensing technologies have been created to enhance early identification and management. While acoustic sensors identify pests by recording the sounds produced during eating or movement in soil and plant tissues, optoelectronic sensors use light-based measures to detect changes in ambient variables associated to pests. Variations in electrical resistance that could point to the presence or activity of pests are measured by impedance sensors. Additionally, by using nanomaterials to increase detection sensitivity, nanostructured biosensors make it possible to identify certain pests or biomarkers linked to plant damage. These technologies offer effective instruments for crop health protection and insect population monitoring [5], [18].

- **Plant stress sensors**: Plant stress is the term used to describe adverse effects on growth brought on by biotic (diseases and pests) and abiotic (drought, salt, and severe temperatures) causes.

These stresses lower crop productivity and jeopardize agricultural sustainability by interfering with physiological and molecular processes. For appropriate management adjustments to be supported and yield losses to be avoided, early stress identification is crucial. Techniques like thermal imaging, spectroscopy, and chlorophyll fluorescence analysis are made possible by modern technologies and allow for non-invasive plant health monitoring. Important information on plant states and environmental elements is provided by sensors that measure soil moisture, salinity, nutrients, and gas exchange. Precision agricultural techniques that maximize resource utilization and boost crop resilience are made possible by sophisticated diagnostic tools that aid in the early detection of stress. Such approaches enhance productivity while supporting sustainable agricultural practices in changing environmental conditions [5], [19].

- **Positional and motion sensors**: Precision agriculture focuses mainly on motion and positioning sensors, which allow precise navigation and automated control of agricultural equipment for tasks as planting, fertilizing, and harvesting.

These sensors facilitate field mapping, real-time machinery tracking, and the operation of autonomous systems, like as drones and tractors, by integrating GPS and IoT technology [20].

Additionally, they make it possible to apply Variable Rate Technology (VRT), which increases resource efficiency and decreases waste by enabling the site-specific delivery of inputs like water, fertilizer, and seeds. Additionally, by reducing fuel usage, chemical overuse, and environmental effect, motion and positioning sensors help to promote sustainability. They promote well-informed decision-making, boost production, and optimize contemporary agriculture methods by offering real-time data and actionable insights [5].

These sensors are the foundation of Internet of Things technology in agriculture because they convert the physical world into digital information that can be sent, processed, and utilized to make decisions. Automation, data processing, and networking are what guarantee that IoT systems run smoothly [5].

DATA TRANSMISSION

Agricultural IoT relies heavily on data transfer, and WSN is a key information transmission channel. Figure 2 represents the data transfer technology frequently utilized in agricultural IoT. The features of various sensor networks vary. When transferring agricultural IoT information, communication technology should be chosen based on the particular project parameters rather than at random [21], [22].

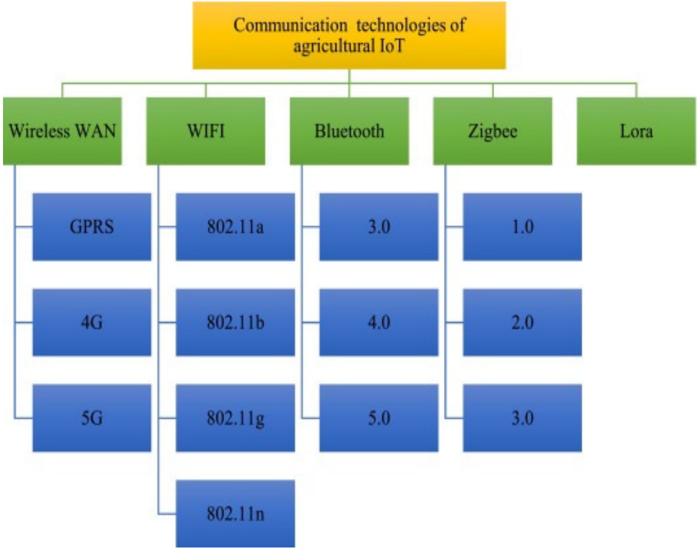

Figure 2. Data transmission technology commonly used in agricultural IoT [21]

DATA ANALYSIS

The collection and analysis of the obtained data is the ultimate goal of information processing. A lot of production data is gathered during the agricultural production monitoring process, and this data has the qualities of being vast, dynamic, and real-time. IoT technology makes it possible to store and analyze production data to some extent and identify related data trends. The storage, computation, and associated processing of large amounts of agricultural production data can be successfully resolved using cloud computing technology, which is mostly utilized for information processing.

Massive agricultural data may be stored, searched, and analyzed using a variety of new cloud service platforms. Strong information analysis skills in artificial intelligence technology can be used for crop harvesting, pest and disease detection, irrigation control, and other tasks. AI can make intelligent decisions by using machine vision, image recognition, and other technologies to make precise judgments and predictions based on the acquired agricultural data. Dynamic Bayesian networks, Kalman filtering, D-S evidence theory, and rough set theory are some of the theoretical approaches used in AI technology today [21].

DISCUSSION

IoT-AI integration in precision agriculture has several advantages, such as increased crop yields, lower costs, labor efficiency, sustainability, and climate adaption. Precise resource application reduces input costs, while accurate yield forecasts and early illness diagnosis boost productivity. Environmentally friendly farming is promoted and waste is decreased through data-driven decision-making. Predictive models assist farmers in proactively adapting to shifting weather patterns, while automated AI-powered solutions reduce the need for manual intervention [5], [23].

The table 1 illustrates how IoT-based technology and conventional agricultural approaches differ from one another. Conventional approaches rely on farmer experience and sporadic observations, which may result in less accurate data and subjective conclusions. IoT systems, on the other hand, employ sensors and algorithms to provide accurate, real-time information through ongoing monitoring.

In contemporary systems, characteristics like temperature, humidity, and vegetation index are collected automatically. In-depth analysis and data-driven decision-making are made possible by this. IoT technologies have greater initial costs, but by optimizing resource usage and minimizing waste, they assist lower costs over time.

Sustainability is a key benefit of IoT systems since the accurate administration of pesticides and fertilizers reduces their negative effects on the environment. Using drones and smart irrigation to automate agricultural processes boosts productivity and decreases the need for human involvement. IoT and AI-based agriculture provides more sustainable and effective solutions than conventional approaches, leading to higher output and better resource management [25].

Table 1. Comparative Table: Conventional Methods vs. IoT-Based Technologies in Agriculture [25]

Specifications	Conventional (Traditional) Methods	IoT-Based Technologies
Operating Principle	Periodic hand measurements, empirical experience, and direct observation	Sensor-based continuous monitoring, automated data collecting, and AI/ML-based analysis
Data Collection	Manual, irregular, and dependent on visual examination	Sensors that measure temperature, humidity, pH, NDVI, and other parameters automatically and in real time
Data Accuracy	Depending on the experience of the farmer, variable	Elevated, measurable, and consistent measures
Decision-Making	Drawing from intuition and experience	Data-driven, with an emphasis on algorithms and predictive models
Initial Cost	Low	High (sensors, cloud platforms, infrastructure)
Long-Term Operational Cost	Potentially higher (waste of resources)	Optimization lowers the use of pesticides, fertilizer, and water
Advantages	-The least amount of money - Simple to put into practice - Technological autonomy	- Continuous monitoring - A higher yield -Cost-cutting - Automated - Traceability
Disadvantages	-Subjectivity -An increased chance of mistakes -Interventions that are delayed	-Expensive upfront expenses -Needs proficiency with digital -Reliance on connectivity
Impact on Sustainability	Higher resource consumption, uniform application	Precision application (VRT), waste reduction, sustainable agriculture
Level of Automation	Low	High (smart irrigation, drones, agricultural robots)
Adaptation to Climate Change	Reactive	Predictive, based on climate models and historical data
Future Perspectives	Will continue in small, traditional farms	Accelerated expansion through digitalization, AI integration, autonomous agriculture

CONCLUSIONS

One crucial step in the digitalization and optimization of agricultural processes is the use of IoT technologies into contemporary agriculture. Real-time cultivation condition monitoring is made possible by the use of sensors, data analytics platforms, and artificial intelligence systems, which enhances resource management and production effectiveness. Farmers can lower their risk of disease and climate stress by making educated decisions based on data collection and analysis on humidity, temperature, nutrients, and plant health.

By optimizing the application of inputs like water, fertilizer, and pesticides, IoT systems support precision agriculture. This promotes sustainable agriculture practices by lowering production costs and their negative effects on the environment. Process automation reduces manual intervention and boosts production. Examples of this include drone-based agricultural monitoring and intelligent irrigation.

The long-term advantages of implementing IoT technologies outweigh the greater upfront expenses and the need for sufficient digital infrastructure. The profitability of agricultural operations is influenced by lowering crop losses, raising yields, and making the best use of available resources. Additionally, the agricultural sector's resilience is increased by predictive technologies that can anticipate climate change and modify agricultural techniques.

In conclusion, IoT and AI-based agriculture is the way of the future for food production, providing creative answers to pressing problems. Adoption of these technologies contributes to the growth of a contemporary and competitive agricultural industry by enabling more effective resource management, increased food security, and greater sustainability.

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