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Transforming Agriculture with the application of the Internet of Agricultural Things (IoAT)

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***Abstract*– The Internet of Things (IoT) has emerged as a transformative technology with the potential to revolutionize agriculture. By connecting devices and sensors, IoT enables real-time monitoring and control of several agricultural parameters, including soil moisture, temperature, and crop health. This research delves into the application of IoT and edge computing in agriculture, focusing on enhancing precision, sustainability, and scalability in the Internet of Agricultural Things (IoAT).**

The study explores diverse range of IoT devices and communication protocols employed in agricultural settings. These technologies facilitate data collection, processing, and analysis, enabling informed decision-making and optimizing resource utilization. Using advanced techniques such as machine learning and artificial intelligence, IoT-powered systems can predict crop yields, detect diseases early, and automate irrigation and fertilization processes.

The findings of this research highlight the significant impact of IoT on agricultural productivity and sustainability. By reducing manual labor, minimizing resource wastage, and improving crop quality, IoT contributes to a more efficient and environmentally friendly farming system. Moreover, the integration of edge computing enables real-time data processing and analysis, reducing latency and enhancing system responsiveness.

Integrating IoT and edge computing offers a promising future for agriculture. By harnessing the power of these technologies, farmers can optimize their operations, increase yields, and mitigate the challenges posed by climate change and resource scarcity. Continued research and development in this field are essential to unlock the full potential of IoT and ensure a prosperous and sustainable agricultural future.

***Keywords*-- IoAT, Smart Farming, Internet of Things, E-Agriculture, Data Collection, Wireless Sensor Networks.**

I. Introduction

With the rapid spread of the Internet of Things (IoT), it has become apparent that different sectors can benefit from the paradigm shift it has brought about, and it is in agriculture where this change is likely to be highly disruptive [1-3]. Given that it is anticipated that the world's population will be about 9.7 billion by 2050, the necessity to develop efficient and eco-friendly production systems is becoming more and more urgent. Climate change, resource depletion, and high productivity needs put pressure on conventional agriculture [4-6].

In this regard, IoT technologies have a strong potential since they permit instant gathering, analysis, and exchange of information between various devices, and this, in turn, makes it possible to improve the farming process and make it more flexible and productive [8-11]. Nevertheless, regardless of the increased involvement and development within this area, a systematic review that addresses the most significant challenges and prospects regarding IoT in agriculture as a whole has been prepared.

Many papers have looked at IoT architectures and communication technologies in particular, but little has been done to develop an overall scheme for the application of IoT in agriculture [12-14]. This especially includes areas such as security issues and the impact that machine learning has on the agricultural sector [15, 16]. Moreover, there is a gap in the literature concerning the systematic treatment of current references on IoT-integrated solutions that would be relevant to the present-day problems of farmers.

The goal of this work is to enhance the understanding of the impact of IoAT (Internet of Agricultural Things). Additionally, these findings will assist in developing new strategies for food production in the increasingly risky conditions that are emerging on a global scale.

Consequently, as agriculture is poised to change in a major way in the future due to digital change, the IoT technologies combined with their potential for impacting the environmental and food security challenges prove fitting agendas. This study aims to present the integration of IoT in agriculture by examining opportunities and outlining the necessary prerequisites for full utilization.

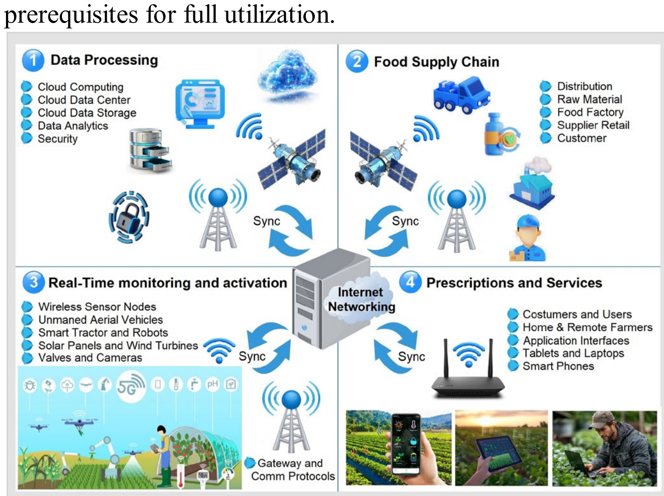

Fig. 1 General ecosystem of IoT structure applied in agriculture.

Fig. 1 shows an example of the IoT ecosystem of the IoT architecture in a smart farm, and the emerging technologies that support it, covered in this review. The ecosystem of the IoT architecture in agriculture involves several fields of application, from real-time monitoring, supervision, and activation of crop variables and processes through data processing to participation in prescriptions and services for farmers, users, and consumers, and even reaching the food supply chain

The paper is structured as follows: Section II presents the IoT framework for agricultural processes, introducing the layers of the IoT architecture and the technologies applied in smart agricultural systems. Section III examines the application fields of IoT in the agricultural sector, illustrating some real-life examples. Section IV describes a series of gaps, problems, and limitations of the IoAT implementation, and analyzes the future of the emerging technologies associated with this area of knowledge. Finally, Section V summarizes the main findings of this study through the conclusions reached.

II. IoT Architecture and Technologies used in Smart Farming

Agriculture is one of the sectors with the greatest potential for adopting and utilizing the *Internet of Things* (IoT). This emerging technology has significantly enhanced processes across various industries, including agriculture. The agricultural sector faces increasing pressure due to population growth, climate change, and the limited availability of energy and water resources. IoT technologies offer innovative methods to improve crop yield and quality, promote environmental sustainability, and enhance energy and production efficiency [1], [3].

As a result, intelligent agricultural systems have emerged, leveraging advanced technologies in sensing, actuation, communication, data processing, user interfaces and apps, information analysis, and machine learning applications. These technologies aim to enhance productivity, optimize resource utilization, and facilitate data-driven decision-making [8-11].

A. The Multi-Layer IoAT Architecture

In general, the architectural framework of the *Internet of Agricultural Things* (IoAT) can be conceptualized as a five-six-layer model [17]. This hierarchy includes the physical or perception layer, the network or communication layer, the intermediate or middleware layer, the analytics and data processing layer, the application layer, and the business layer, as illustrated in Fig. 2. Consequently, each layer is associated with specific communication protocols [18-21]. The primary layers of the IoAT architecture include:

1) Perception Layer: This is the physical layer that forms the foundation of the IoAT architecture, responsible for collecting and transmitting information to and from the agricultural environment. It encompasses sensor and actuator technologies. Sensor devices, such as weather stations, camera modules, and sensor nodes, collect real-time crop data, monitoring meteorological and environmental variables in the soil, air, or plants. These variables include humidity, temperature, luminosity, and other parameters that determine crop health and detect critical conditions such as diseases [18].

Similarly, agricultural robotic platforms, *Unmanned Aerial Vehicles* (UAVs), *Unmanned Ground Vehicles* (UGVs), irrigation systems, autonomous tractors, and other agricultural machinery integrate control boards, sensing and actuation components. Actuators, such as valves and motors, execute automated actions based on sensor data, enabling precise control over farming processes. By gathering real-time data, the perception layer links objects in IoT networks, and provides essential information about crops and their environment, serving as the foundation for further processing, analysis, and informed decision-making [19].

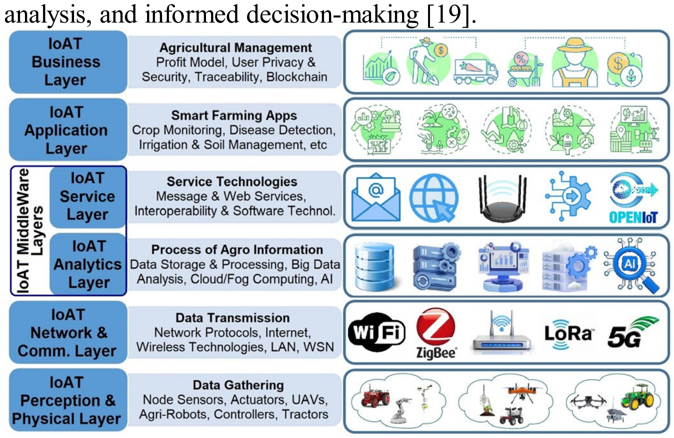

Fig. 2 Five-Layer architecture for an IoAT system.

2) Network Layer: The communication layer is responsible for transmitting the data collected by the perception layer to the cloud or data processing systems. This layer ensures that data is transmitted securely, reliably, and efficiently, enabling real-time monitoring and control of agricultural operations.

The network layer facilitates communication between the perception layer with the middleware layers. It covers several communication systems, which enable data transmission as well as wireless communication technologies such as *Wi-Fi*, *Bluetooth*, *LoRaWAN*, *ZigBee*, *Z-Wave*, *6LowPAN*, *Wireless Sensor Networks* (WSN), and cellular networks (i.e. 4G, 5G) that are commonly used to connect IoT devices in agricultural environments [20].

3) Analytics Layer: This middleware layer, also known as the data management layer, is responsible for processing and analyzing agricultural data to support decision-making. It incorporates cloud and fog computing resources, along with data storage solutions, to aggregate, analyze, and visualize data transmitted from the perception layer via the network layer [17, 21].

Cloud platforms can efficiently handle the large volumes of data generated by IoT devices, providing valuable insights to farmers. Within this layer, advanced algorithms, machine learning models, artificial intelligence applications, big data analysis and visualization tools are employed to extract meaningful information from the information. These technologies enable the prediction of crop performance, the early detection of disease outbreaks, and the optimization of irrigation schedules [18].

The analytics layer serves as a bridge between raw data and actionable insights, due to automation and control of agricultural activities also become possible through the data processing layer facilitating informed decision-making in crop management, energy and water resource allocation, and risk assessment ultimately improving farming productivity and sustainability [19-21].

4) Service Layer: This middleware layer in this work abstracts the software technologies required for developing IoT applications and services in agriculture. Generally, middleware platforms serve as an interface between IoT devices and applications, enabling seamless communication and data exchange. Various design approaches exist for middleware solutions, including application-specific, event-driven, tuple-space, cloud-based, agent-based, virtual machine-based, database-oriented, and service-oriented architectures, among others [21].

5) Application Layer: This is the layer where end users, including farmers and consumers, interact with the IoAT system. It encompasses user interfaces, dashboards, and applications designed to present processed data in an intuitive and accessible manner. Through this layer, farmers and farm managers can monitor real-time information about their crops, equipment, and environmental conditions [17, 18].

Additionally, the application layer integrates decision support systems that generate recommendations based on analyzed data, aiding farmers in optimizing their operations and enhancing productivity. These applications often feature dashboards that display real-time data and analytics, enabling efficient farm management [19, 20].

6) Business Layer: this layer covers the economic and strategic aspects of IoAT. It involves the integration of IoT solutions into existing agricultural practices and business models. This layer focuses on the value proposition of IoT technologies, including cost savings, greater efficiency, and greater sustainability. It also addresses the challenges of implementing IoAT solutions, such as data privacy, security concerns, and the need for training and support for farmers [22].

B. *Enabling Technologies of IoAT Systems*

The integration of IoT in agriculture represents a transformative shift in farming practices. The essential components of the IoAT can be categorized into hardware and software resources, which, when combined with communication protocols, enable efficient data transmission, processing, analysis, and management. These components help farmers optimize operations, enhance productivity, and ensure sustainability. IoAT hardware resources include sensor and actuator technologies, communication system modules, and computing and physical storage devices.

These components are substantive for data collection, transmission, tracking, and control in precision agriculture. Figure 3 illustrates the synthesis of enabling technologies in IoAT systems. Similarly, software components play a fundamental role in data management, processing, analysis, and visualization, while also facilitating user interaction for farmers. These informatics resources encompass user interface tools, mobile applications, data analysis software, and crop management platforms powered by machine learning algorithms. Additionally, security and privacy technologies are integral to ensuring data protection and system reliability.

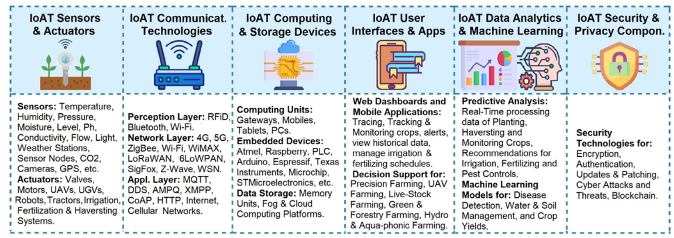

Fig. 3 Technologies used in IoT for agricultural systems.

1) Sensors and Actuators Technologies: Sensors and actuators are fundamental components of IoAT systems, positioned within the perception layer of the IoAT architecture. Sensors serve as primary data collection elements, while actuators execute actions based on real-time decision-making in agricultural processes [11, 19, 20]. A wide variety of sensors are employed in IoAT applications, categorized based on agricultural use, measured physical variables, and underlying technologies [23, 24]. Table I summarizes the sensor technologies used in IoAT systems, detailing their type, application, and operational principles [25, 26].

TABLE I
SENSORS IOAT AND ITS APPLICATIONS

Sensor Type	Applications	Operation Principle
Acoustic	Pest monitoring and detection. Classifying Seed and Fruit varieties.	Measuring the variations in noise level when intermingling with other materials.
Airflow	Soil air permeability and penetration., Soil moisture.	Generating ultrasonic waves and differential pressure measurement.
Carbon Dioxide	Quantifying exchanges of CO_2, water vapor, methane, or other gases in the air.	Eddy Covariance-Based. Measuring continuous flux over large areas.
Dielectric	Measurement of soil moisture an moisture level.	Capacitive effect between two plates.
Electrochemical	To analyze soil nutrient levels and pH. N, P, K. Substrate monitoring.	Measuring nutrients in soil, with salinity, and pH sensors.
Electromagnetic	Recording electrical conductivity, residual nitrates, and organic matter in soil.	Measure the capability of soil particles to conduct or accumulate electrical charge.
Electronic	Calculating in real-time, plant transpiration, irrigation, and humidity.	Field Programmable Gate Array (FPAA) Based in digital electronics blocks and chips.
Force	Force and torque sensing in mechanical components and agriculture machinery.	Strain Gauges, load cells, using piezoelectric effect. Accelerometers and IMUs..
GPS	Monitoring Crops, yield maps of fields, fertilizing, harvesting, Guidance UAVs/UGVs..	Global Positioning Systems work by receiving signals from a network of satellites.

Sensor Type	Applications	Operation Principle
Humidity	Environmental monitoring, soil management, irrigation scheduling. Evapotranspiration	Amount of water vapor present in the air and level of water in the soil. Lysimeters.
Light Intensity	Greenhouse Automation, Monitoring Plant Health, Automated Irrigation.	Photovoltaic effect, work by converting light energy into an electrical signal.
Light Detection and Ranging (LIDAR)	Land mapping, soil type determination, farm 3D modelling, erosion monitoring.	Emit pulsed light waves and bounce off when colliding with objects and are returned.
Mass Flow	Yield monitoring, Irrigation Management, Fertilizer Application, Pesticide Spraying	Flowmeters that use the Coriolis flow effect or thermal mass flow effect.
Mechanical	Soil compaction or mechanical resistance. Soil Compression. Soil management.	Record the force assessed by strain gauges or load cells.
Optical	Soil organic substances, soil color, minerals, composition, clay content, Fruit maturation.	Sensors use light reflectance phenomena to measure changes in wave reflections
Optoelectronic	Detect weeds, crop and soil status, diseases or pest monitoring and detect objects.	Vision sensors differentiate based on reflection spectra. Visible range and Multispectral cameras.
Telematics	Assessing location, travel routes, and machine and farm operation activities.	Telecommunication between places (especially inaccessible points.
Temperature	Crop monitoring and yield, Greenhouse Climate Control, Soil Monitoring, plant health, Weather Monitoring.	Thermoresistive effect in RTDs, thermoelectric effect in Thermistors, Seebeck effect in thermocouples.
Ultrasonic	Tanks level, spray distance measurement, uniform spray coverage, object detection, monitoring crop canopy.	Uses a transducer to send and receive ultrasonic pulses that relay information about an object's proximity .
Remote Sensing	Crop assessment, yield modeling, forecasting yield date, land cover and degradation mapping, forecasting, the identification of plants and pests, etc.	Satellite-based sensor systems collect, process, and disseminate environmental data from fixed and mobile platforms.

Actuators are devices that execute actions based on sensor data. For instance, in irrigation systems, actuators control valves and regulate water flow according to soil moisture levels detected by sensors. This automation not only saves time but also optimizes resource usage, reducing waste and enhancing crop yields [4, 12, 16, 17, 22, 25, 26-28]. Key actuator applications in IoAT systems include Automated Irrigation Systems, Fertilization Systems, Aerial and Ground Robotics, and Automated Agricultural Machinery.

2) Communication Technologies: Communication devices exchange data between sensors, actuators, and central processing units. In IoAT systems, communication technologies are primarily wireless and transversal across all architecture layers, each with specific protocols and modules. Various wireless communication technologies exist, each with distinct advantages and limitations [4, 5, 13].

The selection of a communication technology is crucial, as it directly impacts the scalability, reliability, and overall performance of an IoAT system. Farmers must consider coverage area, data transmission frequency, and power consumption when choosing the most suitable technology for their agricultural IoT applications. Table II summarizes the key wireless communication technologies used in IoAT systems, linking physical elements of the perception layer with the network layer [2, 4, 5, 12, 17, 18, 25]. The most relevant technologies include:

TABLE II
COMMUNICATION WIRELESS TECHNOLOGIES USED IN IOAT

Protocol	Standard	Range*	Frequency	Data Rate	Power
RFID	Numerous	SR 1 m	13.56 MHz	423 Kbps	1 mW
Bluetooth	IEEE 802.15.1	SR 10 m	2.45 GHz	1–3 Mbps	1 W
ZigBee	IEEE 802.15.4	SR 20 m	2.4 GHz	250 Kbps	1 mW
Z-Wave	Z-Wave	SR 30 m	908.42 MHz	100 Kbps	1 mW
Wi-Fi	IEEE802.11.x	SR 100 m	2.4 GHz – 60 GHz	1.2 Mbps – 6.75 Gbps	1 W
6LowPAN	IEEE 802.15.4	SR 100 m	908.42 MHz – 2.4 GHz	20 Kbps – 250 Kbps	1 mW
LoRaWAN	LoRaWAN	LR 10 Km	Many	0.3–50 Kbps	Very low
WiMAX	IEEE 802-16	LR 50 Km	2.5–5.8 GHz	0.4–1 Gbps	1 W
SigFox	SigFox	LR 50 Km	908.42 MHz	10–1000 bps	Very low
NB-loT	3GPP	LR 15 Km	180 KHz	200 Kb/s	Very low
2G	GSM	CA 26 Km	850–1900 MHz	171–384 Kbps	1–3 W
3G	UMTS	CA 26 Km	850–1900 MHz	0.73–56 Mbps	1–4 W
4G	LTE	CA 28 Km	700–2600 MHz	0.1–1 Gbps	1–5 W
5G	ITU IMT-2020	CA 28 Km	0.7–72 GHz	20 Gbps	1–5 W

* SR – Short Range, LR – Long Range, CA – Cellular Area.

- Cellular Networks: For applications requiring extensive coverage, cellular networks offer a reliable solution for IoAT applications. They enable real-time data transmission over long distances, making them ideal for remote farming operations where Wi-Fi connectivity is unavailable. 4G and 5G networks, as next-generation technologies, provide high-speed, low-latency communication, enabling real-time monitoring and control of agricultural systems [4, 5, 17, 30].

In the application layer of the IoAT architecture, standardized communication protocols are essential for ensuring interoperability across devices and platforms [4, 12, 19, 25, 26]. Key protocols include:

- MQTT (*Message Queue Telemetry Transport*): A lightweight messaging protocol designed for high-latency, low-bandwidth networks. It is particularly suited for agricultural IoT applications, as it enables efficient communication while minimizing data consumption.

- CoAP (*Constrained Application Protocol*): A specialized web transfer protocol designed for use in resource-constrained networks and IoT devices. It supports simple yet efficient communication, making it ideal for agricultural applications requiring low overhead and energy efficiency.

- HTTP/HTTPS (*Hypertext Transfer Protocol*): While not specifically designed for IoAT, these widely used internet communication protocols are often leveraged in cloud-based agricultural IoT applications to facilitate data exchange between field devices and cloud platforms.

- XMPP (*Extensible Messaging and Presence Protocol*): A protocol that enables real-time, bidirectional communication between devices and applications, facilitating instant interaction and remote control of agricultural systems. XMPP also integrates security mechanisms to protect transmitted data.

- AMQP (*Advanced Message Queuing Protocol*): A protocol that enables asynchronous communication between devices and applications, ensuring that messages are stored in queues and delivered when the recipient is available. This enhances the reliability and scalability of agricultural IoT systems, particularly in environments with intermittent connectivity.

3) Computing and Storage Devices: Data processing and storage are essential for managing the large volumes of data generated by IoAT devices. Once data is collected and transmitted, it must be processed and stored for subsequent analysis and decision-making. This is where computing units, embedded systems, cloud computing, and edge computing play a crucial role [11, 12, 17, 32, 33].

Computing units' process sensor-generated data and make decisions based on predefined algorithms. These units can be located near the sensors or remotely and typically include conventional computing devices such as smartphones, tablets, and gateways. Additionally, microcontroller-based computing platforms or *Single Board Computers* (SBCs) are widely used in IoAT systems. Most of these processor boards integrate a Wi-Fi module with TCP/IP support, allowing seamless connectivity to any Wi-Fi network.

These systems enable the rapid integration of various sensors via GPIO pins, facilitating scalability and multi-sensor integration on a single platform. Thanks to this capability, SBCs can function as gateways or core nodes in IoT architectures [32]. Moreover, these programmable hardware boards offer high scalability, low power consumption, and developer-friendly IDEs. One of their key advantages is support for multiple programming languages, including Python, which allows for the flexible and efficient development of IoT applications.

In agriculture, these SBCs are widely used for monitoring various environmental parameters in farms and greenhouses, including irrigation, water quality control, and automation of agricultural equipment. Specifically, IoT-based control systems have been instrumental in maintaining optimal growing conditions and ensuring high-quality crop production. Table III summarizes the key characteristics of these processor boards for process control in IoT-based smart agriculture [11, 32].

TABLE III
AVAILABLE IOAT COMPUTING UNITS

Platform	Processor	OV* (V)	CS* (MHz)	BW*	SM*	CPS*	LPS*	GPIO
Arduino	ATMega32	5, 3.3	16	8	2 KB	Wi-Fi ZigBee Ethernet, Bluetooth	Python Scratch Wiring	SPI, I^{2}C, UART, GPIO
Raspberry Pi	Broadcom BCM2835	5	700	32	512 MB	Wi-Fi ZigBee Ethernet, Bluetooth	Python C, C++ Scratch Wiring	SPI, DSI, SDIO, UART, GPIO
Microchip	PIC18F458	5	40	8	32 KB	Wi-Fi ZigBee Ethernet, Bluetooth	C, Assembler, Wiring	SPI, I^{2}C, UART, CAN, GPIO
Espressif	ESP8266 L106 RISC	3.3	80	32	32 KB	Wi-Fi ZigBee	Python, RTOS, ESP-Open	SPI, UART, GPIO
Intel Edison	IIntel QuarkTMSoC X1000	3.3	100	32	1 GB	Wi-Fi ZigBee Ethernet, Bluetooth	C, C++ NodeJS Wiring	SPI, I^{2}C, UART, GPIO
BeagleBone	Sitara AM3358B	3.3	1000	32	512 MB	Wi-Fi ZigBee Ethernet, Bluetooth	Python C, C++ Perl, Java Ruby	SPI, I^{2}C, UART, GPIO, McASP

* OV – Operating Voltage, CS – Clock Speed, BW – Bus Width, SM – System Memory, CPS – Communication Protocols Supported, LPS – Language Programming Supported.

One of the main limitations of CBS devices is their restricted storage capacity. Consequently, data is transmitted and stored in the cloud, ensuring scalability and accessibility for IoAT applications.

\- Cloud Computing: Cloud platforms offer scalable processing and storage capabilities, enabling the aggregation of large volumes of data from multiple sources. With the rise of the IoT, which connects billions of devices to the Internet, it is essential not only to compute, store, and execute applications but also to process vast amounts of incoming data from various interfaces, including sensors and user inputs [4, 5].

Advanced analytics and machine learning algorithms can be applied in the cloud to extract valuable insights from agricultural data, such as predicting crop yields or detecting disease outbreaks. Among the most widely used cloud platforms in IoAT applications are Amazon Web Services (AWS), Microsoft Azure (FarmBeats), Mobius, ThingSpeak, and Google Cloud (OpenAg and AgroSar) [17, 18].

These platforms support several agricultural IoT applications, providing hosting, analytics, and visualization services. ThingSpeak has become the most widely adopted cloud-based platform in IoAT applications, primarily due to its open-source nature and low technological requirements for sensor integration and data retrieval over the Internet. These cloud platforms provide farmers with critical information regarding plant health, water resource availability, and crop performance indicators [25].

\- Databases: IoAT data is typically stored in databases optimized for time-series data, as IoT data often consists of measurements timestamped over time. Some of the most popular databases for IoT applications include InfluxDB, TimescaleDB, and Cassandra [17, 18]. Users can leverage Arduino, Raspberry Pi, and BeagleBone to transmit sensor data and create dedicated data storage channels. This database infrastructure serves as the foundation for IoT-based smart agriculture applications, facilitating efficient data management and analysis.

\- Edge and Fog Computing Devices: In real-time processing scenarios, Edge Computing is employed to analyze data locally at the source, minimizing the need for continuous cloud communication and enabling faster decision-making. This approach processes data closer to the source (i.e., at the network edge), thereby reducing latency and optimizing bandwidth usage [17, 18, 25]. For example, edge devices can process sensor data locally and trigger immediate actions, such as activating irrigation systems when soil moisture levels drop below a predefined threshold. By implementing Edge/Fog Computing, IoAT systems can enhance efficiency, responsiveness, and autonomy, particularly in rural and remote agricultural environments where connectivity limitations may pose challenges.

4) User Interfaces and Apps: The application layer of IAoT systems serves as the primary point of interaction for end users, enabling seamless engagement with agricultural technology. User interfaces, dashboards, and mobile applications play a critical role in presenting agricultural data in an intuitive and actionable manner, allowing farmers to efficiently monitor and control their operations [31, 33, 34]. The key user interfaces and applications employed in IoAT systems include:

- Dashboards: These visual interfaces aggregate data from multiple sensors and display real-time information. Farmers can monitor key metrics such as soil moisture, temperature, and crop health through intuitive graphical representations, enabling quick and informed decision-making.

- Mobile Applications: Mobile apps provide farmers with the flexibility to access data and control systems remotely. They can receive alerts, view historical trends, and manage irrigation or fertilization schedules directly from their smartphones, enhancing convenience and responsiveness [35].

- Web-Based Applications: Web applications allow farmers to access agricultural data from any device with Internet connectivity. These platforms frequently incorporate advanced analytics, enabling users to visualize data trends and make data-driven decisions. Several web-based applications serve as farm management and decision-support systems, utilizing data analytics to generate actionable insights and recommendations. For instance, a decision-support system can analyze weather forecasts, soil conditions, and crop growth patterns to recommend optimal planting schedules or efficient irrigation strategies [36].

5) Data Analytics and Machine Learning (ML): These tools are essential in transforming raw data into actionable insights, enabling farmers to make data-driven decisions [4, 12]. These technologies support predictive modeling, trend analysis, and real-time optimizations in agriculture.

- Predictive Analytics: analytics applies statistical techniques, probabilistic models, and artificial intelligence to analyze historical agricultural data, such as time series or past imagery, to forecast crop yields, pest infestations, and plant diseases [17–19]. By identifying patterns, these tools enable proactive decision-making, reducing potential losses. Several IoAT-based predictive analytics tools have been developed, including AgriPrediction, Tableau, and IBM Watson IoT. These platforms integrate wireless technologies such as LoRa and offer data visualization to facilitate interpretation for farmers.

- Machine Learning Algorithms: ML algorithms analyze large-scale IoAT data to detect trends and correlations, assisting farmers in optimizing agricultural practices [4, 25]. These models continuously learn from data patterns, enhancing decision-making in areas such as Irrigation optimization based on weather forecasts, soil condition assessment for crop health monitoring, and recommendation of optimal planting times and crop varieties.

ML techniques are broadly classified into three categories: Supervised Learning, where models are trained on labeled datasets, where input-output relationships are predefined; Unsupervised Learning, where patterns are extracted from unlabeled data, identifying hidden structures in datasets; and Reinforcement Learning, what are algorithms do not require labeled data but learn through trial and error, receiving rewards based on performance [4, 37]. Several ML algorithms have been developed for IoT-driven agricultural applications, each tailored to specific farming challenges.

Machine learning (ML) are an emergent technology in modern agriculture by enabling predictive modeling, classification, and decision-making. *Decision Trees* (DTs) are widely used for classification (e.g., crop identification) and regression (e.g., yield estimation) [37-41]. They assist in tasks like yield prediction, weed detection, and soil-based crop recommendations. *Random Forest* (RF), an ensemble of DTs, improves accuracy and reduces overfitting, making it effective for disease detection, soil property estimation, and crop classification [38,40].

Support Vector Machines (SVMs) are applied in classification and regression by constructing hyperplanes to separate data points. Their ability to handle high-dimensional data makes them useful for plant disease detection, yield prediction, and satellite image analysis [37-39]. *K-Nearest Neighbors* (k-NN) classifies data based on similarity but has high computational costs, limiting its scalability. It is used for disease detection, soil classification, and drought prediction [39-41].

Artificial Neural Networks (ANNs) and Deep Learning (DL), including CNNs, RNNs, and LSTMs, enable advanced image-based applications such as crop recognition, fruit counting, and irrigation management [36-41]. These models improve accuracy in complex agricultural scenarios by learning intricate patterns in data.

Decision Support and Simulation Systems integrate ML with IoT data from sensors and drones to optimize farming practices. These systems analyze weather, soil conditions, and crop growth to provide actionable recommendations. Simulation tools, such as DSSAT and APSIM, help predict agricultural outcomes, allowing farmers to test strategies virtually before implementation, reducing risk and improving resource allocation [38, 39].

- Big Data Analytics: The IoAT connects thousands of devices and systems across agriculture and supply chains, generating massive amounts of data from diverse sources, including sensors, UAVs/UGVs, and mobile crowd-sensing systems. This data is processed and analyzed to extract valuable insights that support real-time decision-making in agricultural processes [41-43]. Big Data Analytics addresses critical challenges such as food security and sustainability, transforming raw data into actionable knowledge to enhance agricultural efficiency and resilience.

6) Security and Privacy Components: As IoT systems in agriculture become increasingly prevalent, ensuring data security and privacy is paramount [12, 44, 45]. To achieve these targets different technologies and practices are implemented, including:

- Encryption: Data transmitted between devices and cloud platforms is often encrypted to prevent unauthorized access. This ensures that sensitive information, such as crop yields and agricultural practices, remains confidential [44-46].

- Authentication: Robust authentication mechanisms are essential to verify the identity of users and devices accessing the system. This prevents unauthorized control of agricultural equipment and data tampering [44-46].

- Regular Updates and Patches: Keeping software and firmware up to date is crucial for protecting IoT systems from vulnerabilities. Frequent updates mitigate security risks and ensure systems remain equipped with the latest features and protections [44-46].

- Blockchain Technologies: provides a secure and transparent approach to managing agricultural data, offering key benefits such as data integrity, reliability, and traceability [12]. Data integrity ensures that information collected from IoT devices remains tamper-proof, making it a reliable source for decision-making. Meanwhile, data traceability enables end-to-end tracking of agricultural products, from farm to table, enhancing food safety and quality assurance.

III. Applications of IoT in Agriculture

The integration of IoT systems in agriculture represents a paradigm shift toward smarter and more efficient farming practices. As the global population continues to grow, the demand for food production increases, necessitating innovative solutions to enhance agricultural productivity, resource efficiency, and environmental sustainability. IoT-based Agricultural Technologies (IoAT) leverage interconnected devices to collect and exchange real-time data, offering transformative applications that significantly improve farming practices [2, 4, 5, 11]. These applications can be categorized into four main areas (See Figure 4):

- *Precision Agriculture and Resource Management*: IoAT enables the management of agricultural systems, including water use, crop monitoring, irrigation, soil nutrients, environmental conditions, and waste management [17-19].

- *Environmental and Crop Monitoring*: IoAT facilitates the real-time monitoring of plant growth, soil conditions, irrigation, fertilization, pest control, and hydroponic/aquaponic systems [18-20].

- *Automated Agricultural Control Systems*: IoAT supports the control of key variables such as temperature, humidity, irrigation, water quality, nutrient supply, and pesticide application [19-21].

- *Autonomous Agricultural Machinery*: IoAT enhances the supervision and operation of unmanned agricultural equipment, including tractors, UAVs, UGVs, agricultural robots, and autonomous rovers [26-28].

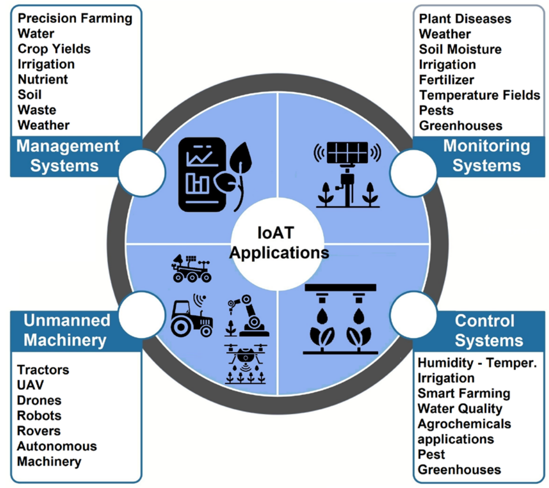

Fig. 4 Applications Fields of the Internet of Agricultural of Things IoAT.

The following sections explore the key applications of IoT in agriculture, highlighting its benefits and implications for the future of food production [47-50, 53].

A. *Precision and Smart Farming*

IoAT technologies enable precision farming, allowing farmers to monitor soil conditions, crop health, and environmental factors in real-time. This data-driven approach optimizes resource allocation, leading to higher yields and lower operational costs. IoT devices, such as sensors and drones, are used to assess and manage crop variability within fields. By collecting real-time data on soil conditions, moisture levels, and plant health, farmers can make informed decisions that enhance resource efficiency. This not only improves crop yields but also reduces environmental impact, promoting more sustainable farming practices [1, 2, 5, 7, 11, 14, 16-18, 47].

Smart farming systems have been successfully implemented across various crops and regions, utilizing IoT-enabled sensor networks to gather data on soil temperature, humidity, and crop development. By analyzing this data, farmers can optimize fertilization, irrigation, and pest control strategies, significantly boosting crop productivity.

B. *Automated Irrigation Systems*

These systems exemplify a practical IoT application that addresses the critical challenge of water management in agriculture. These systems use soil moisture sensors and meteorological data to determine the optimal irrigation schedule. By automating the irrigation process, farmers can ensure that crops receive the right amount of water at the right time, improving crop health and reducing water consumption [31-33, 35, 42].

Case studies have demonstrated that farms implementing IoT-based smart irrigation systems achieve significant water savings while maintaining or even increasing crop yields. This application is particularly beneficial in large-scale agricultural regions facing water scarcity or prolonged droughts. Reports indicate that automating irrigation can reduce water usage by up to 30%, while simultaneously enhancing crop productivity.

C. *Crop Monitoring and Management*

IoT systems enable comprehensive crop monitoring, allowing farmers to track plant health and growth in real-time. By integrating sensors, drones, and satellite imagery, farmers can collect environmental data on temperature, humidity, and light levels. This information is crucial for identifying potential issues, such as pest infestations or nutrient deficiencies, before they escalate. For instance, drones equipped with multispectral cameras can analyze plant reflectance, providing farmers with actionable insights to optimize crop management strategies [8, 9, 10, 47, 48].

D. *Livestock Management*

The application of IoT in livestock management is another area where technology is making a substantial impact. IoT devices, such as smart collars, wearable sensors, and GPS trackers, allow farmers to continuously monitor animal health and behavior. These devices track vital signs, activity levels, and location, enabling early detection of health issues and prompt intervention [48-50].

For example, if a cow exhibits signs of distress or abnormal behavior, farmers can take immediate action, potentially saving the animal's life and reducing economic losses. Additionally, IoT systems optimize feeding practices by tracking grazing patterns and nutritional intake, leading to improved herd health and increased milk production.

E. *Supply Chain Management*

Another key IoT application is the real-time tracking of agricultural products from farm to market. IoT systems enhance transparency and traceability across the supply chain, which is crucial for ensuring food quality and safety [28, 46, 48-50].

For instance, temperature and humidity sensors monitor storage and transport conditions of perishable products, alerting stakeholders to deviations that could compromise quality. By improving supply chain efficiency, IoT applications help reduce food waste and enhance overall sustainability in agricultural operations.

F. *Disease and Pest Detection*

Early detection of crop diseases and pest infestations is essential to ensure high yields and prevent losses. IoT-based systems equipped with advanced sensors and imaging technologies continuously monitor environmental conditions and detect anomalies that may indicate the presence of pests or diseases [4, 5, 48-51].

For example, smart traps can collect and analyze pest population data, allowing farmers to implement targeted control measures. This proactive approach not only reduces the need for chemical pesticides but also promotes healthier ecosystems. By leveraging IoT for disease and pest detection, farmers can protect their crops while minimizing environmental impact.

G. *Smart Greenhouses, Hydroponics, and Aquaponics*

Smart greenhouses represent a cutting-edge IoT application in agriculture. These controlled environments utilize IoT devices to monitor and regulate key factors, such as temperature, humidity, and light levels, ensuring optimal growth conditions for plants [9, 26, 49, 52].

Automated systems adjust ventilation, irrigation, and lighting in real-time, providing crops with ideal conditions throughout their growth cycle. This precision control enhances productivity and reduces resource consumption, making smart greenhouses a promising solution for sustainable agriculture. the demand for food production escalates, necessitating innovative solutions to enhance agricultural productivity.

IV. Challenges, Limitations and Future Directions of IoAT Implementation

While hardware tools, simulation platforms, and IoAT software solutions have significantly improved agricultural practices, several challenges persist. Integrating data from diverse IoT devices is complex, and ensuring data accuracy is a determinant for reliable simulations. Additionally, user-friendly interfaces are essential to encourage adoption among farmers with varying levels of technological expertise [2, 4, 5, 12].

Looking ahead, advancements in agricultural simulation tools rely on the continuous integration of cutting-edge technologies such as artificial intelligence (AI) and machine learning (ML). These technologies can enhance predictive capabilities, enabling more precise simulations and better decision-making. Furthermore, the development of open-source platforms can foster collaboration and innovation within the agricultural community, driving the evolution of IoAT-enabled solutions [17-19].

A. *Connectivity Issues*

One of the primary challenges in IoT adoption for agriculture is connectivity. Many agricultural operations are located in rural areas where internet access is limited or unreliable. The effectiveness of IoT systems depends heavily on the seamless transmission of data between devices and cloud platforms. In regions with poor connectivity, farmers may struggle to access real-time data, undermining the benefits of IoAT applications [17, 18, 25].

Moreover, deploying IoT devices often requires a robust network infrastructure, which may not be feasible in remote agricultural settings. Unstable connectivity can lead to data loss, delays in decision-making, and ultimately reduced productivity. Addressing connectivity challenges is crucial for the successful implementation of IoT technologies in agriculture, necessitating investments in infrastructure and innovative solutions to improve rural connectivity.

B. *High Implementation Costs*

The initial investment required for IoAT deployment represents a significant barrier, particularly for small-scale farmers. The costs associated with purchasing sensors, communication devices, and cloud services can be prohibitively high, especially for those with limited financial resources. Additionally, ongoing operational and maintenance costs further contribute to the financial burden on farmers [18, 19].

Although IoT technologies offer long-term cost savings and increased productivity, high upfront costs may discourage adoption. Financial constraints restrict access to advanced technologies, perpetuating a digital divide within the agricultural sector. To encourage widespread adoption, it is essential to explore financing options, government subsidies, and cost-effective solutions tailored to farmers' needs.

C. *Security and Privacy Concerns*

As with any technology that relies on data collection and transmission, security and privacy concerns are paramount in IoT-based agriculture. The interconnected nature of IoT devices makes them vulnerable to cyberattacks, potentially compromising confidential data and disrupting agricultural operations. Farmers may hesitate to adopt IoAT technologies due to concerns about data breaches or unauthorized access to sensitive information [17, 18, 25].

Additionally, the collection of personal and operational data raises privacy issues, particularly when shared with third parties without consent. Implementing robust security measures and transparent data management practices is essential to building trust among farmers and encouraging the adoption of IoT solutions.

D. *Interoperability Challenges*

The agricultural sector features a wide range of IoT devices and platforms, each with distinct protocols and standards. This lack of interoperability complicates system integration, leading to inefficiencies and increased complexity.

Farmers often struggle to connect devices from different manufacturers, resulting in fragmented data and limited functionality. The absence of standardized protocols hinders seamless information exchange, reducing the overall effectiveness of IoT applications. Developing universal standards and protocols is crucial to enabling effective communication and collaboration among IoT devices.

E. *Resistance to Change*

The agricultural sector is traditionally conservative, with many farmers still relying on long-established practices and methods. The adoption of IoAT technologies requires a cultural shift, as farmers must be willing to embrace new technologies and adapt their workflows [19, 25, 28].

Resistance to change may stem from a lack of awareness of IoAT benefits, technological skepticism, or concerns about complexity. Older generations of farmers, in particular, may be less inclined to adopt digital solutions, creating a generational divide in IoT adoption. Educational and training programs are essential to demonstrating the value of IoT technologies and equipping farmers with the skills needed to leverage these innovations effectively.

F. *Environmental and Technical Limitations*

The deployment of IoT devices in agricultural settings is subject to various environmental and technical constraints. Factors such as extreme weather conditions, soil types, and terrain can impact device performance and durability. For instance, sensors may be susceptible to damage from adverse weather, pests, or even theft, leading to higher maintenance costs and downtime [17, 18, 4].

Moreover, the effectiveness of IoAT applications is influenced by specific agricultural contexts, including crop types and farming practices. Adapting IoT solutions to meet the unique needs of diverse agricultural environments is crucial for maximizing their effectiveness. This requires ongoing research and development to create robust, adaptable IoT systems capable of withstanding agricultural challenges [54-56].

Many farmers lack the technical expertise or necessary resources to interpret complex datasets, leading to underutilization of collected information. Moreover, integrating data from multiple sources can be cumbersome, requiring sophisticated data management systems. Without effective data analysis, the full potential of IoT technologies may not be realized, hindering informed decision-making and strategic planning.

V. CONCLUSIONS

The integration of IoT technologies is transforming agriculture by enabling data-driven decision-making, optimizing resource use, and improving overall efficiency. Precision farming benefits significantly from real-time monitoring of soil conditions, weather, and crop health, allowing for targeted interventions like smart irrigation and fertilization. These advancements enhance crop yields while minimizing waste and environmental impact.

In irrigation management, IoT-driven systems automate water distribution using soil moisture sensors and weather forecasts. This is particularly beneficial in water-scarce regions, where smart irrigation has proven to reduce water consumption and operational costs, promoting sustainable agricultural practices. Similarly, in livestock management, IoT-enabled wearable devices facilitate real-time monitoring of animal health and behavior, ensuring early disease detection, improved productivity, and ethical farming practices.

Beyond the farm, IoT enhances supply chain efficiency by providing real-time insights into inventory, transportation conditions, and market demand. This reduces food waste, improves product quality, and strengthens supply chain resilience. However, widespread adoption still faces challenges such as high implementation costs, connectivity limitations in rural areas, data security concerns, and interoperability issues. Addressing these barriers requires collaboration among policymakers, technology developers, and farmers to develop cost-effective solutions and establish industry standards.

To maximize IoT's potential in agriculture, ongoing investment in research, infrastructure, and farmer education is essential. Advancing AI-driven analytics, enhancing cybersecurity, and fostering multi-stakeholder collaboration will be key to building a more efficient, sustainable, and technology-driven agricultural ecosystem.

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