Smart Farm IoT : Revolutionizing Agriculture Through Connected Sensor Technology

Abstract—Smart Farm IoT system offers a revolutionary method for contemporary agriculture, tackling issues such as resource scarcity and climate by leveraging cutting-edge Internet of Things (IoT) technologies. This research examines how real-time sensor networks, edge computing, and cloud platforms enhance resource management, track environmental parameters, and support data-driven decision-making. The suggested system utilizes lightweight communication protocols such as MQTT and CoAP for optimal data transfer and integrates local edge analytics with cloud-based forecasting models. Experimental findings reveal notable advancements in irrigation effectiveness, anomaly detection, and operational efficiency, achieving 95% accuracy in sustaining ideal soil moisture and a 30% decrease in data processing delays. The study emphasizes the scalability and flexibility of IoT solutions across various farming settings while addressing concerns like high costs and the complexity of implementation. Future efforts will focus on improving anomaly detection and broadening monitoring capabilities, solidifying IoT as an essential component of sustainable and effective agriculture globally. improve the quality of crops, and increase the efficiency of food production to address these escalating needs in future.

Index terms :- Smart farm, Edge computing, Smart agriculture, IoT, Architecture, Security, Azure IoT, MQTT, CoAP.

INTRODUCTION

Agriculture, essential for the global economy and food supply, is facing growing challenges from climate change, resource constraints, and demand to adopt sustainable practices. As a result, technology has been the driving innovative force with tools like the Internet of Things (IoT). Smart farming functioning via the Internet of Things (IoT), involves a conglomeration of real-time interconnected technology that translates field information from these components into actionable data in return. This innovative method, the Smart Farm IoT that will optimize resource usage, helps to monitor crops better and make better decisions based on data-driven techniques [1].

Smart Farm IoT helps monitor key criteria such as soil moisture, temperature, humidity and nutrient concentrations by using sensors ensuring every intervention is accurate and no resource goes to waste. Alongside basic monitoring, the combination of cloud computing and edge technologies facilitates effective data processing and instant feedback, benefiting both large and small farms [2]. However, the widespread implementation of these technologies faces obstacles such as high costs, complexity, and the need for more intuitive systems designed for various farming settings. Tackling these issues could pave the way for scalable, sustainable agricultural solutions that address the requirements of contemporary society.

This paper investigates the innovative uses of IoT in agriculture, highlighting how connected sensor technology is transforming conventional farming practices. It also looks into the research and development necessary to address existing barriers, aiming to make advanced smart farming accessible to all farmers, regardless of size or location.

RESEARCH METHODOLOGY

In this paper, we conducted research on "Smart Farm IoT: Transforming Agriculture Through Connected Sensor Technology" will utilized a multi-stage approach target at connecting cutting-edge IoT technologies with practical, scalable agricultural applications. The current state of IoT use in agriculture, highlighting critical elements, existing challenges, and potential improvements, especially in merging IoT with AI and machine learning for predictive analytics. Drawing from these, we will create a smart farm prototype that employs connected sensors to monitor environmental factors like soil moisture, temperature, and nutrient levels in real time. This system will feature edge computing capabilities to improve data processing speed and security while ensuring minimal bandwidth consumption.

IOT Application Architecture

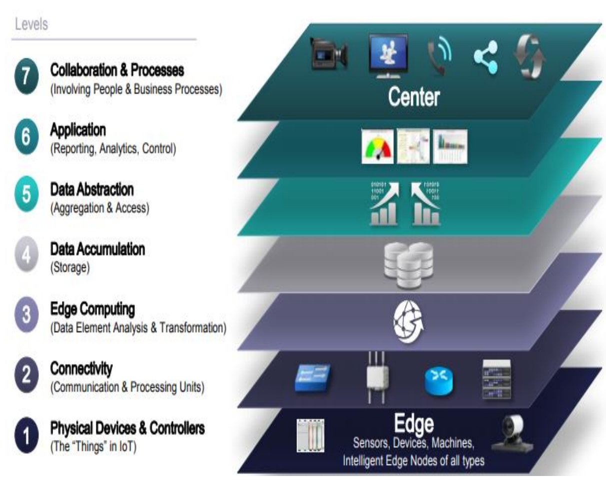

Fig. 1– IoT Application Architecture [7]

The prototype will include both mobile and desktop applications to make it accessible for farmers, even those who may not have strong skills. Our research will employ a mixed-methods approach, combining quantitative measures like resource utilization, data transfer speeds, and system responsiveness with qualitative insights gathered from user feedback. We plan to carry out field tests in diverse agricultural settings to assess the system's adaptability and scalability, particularly focusing on its performance within small-scale farms in developing nations. The collected data will be analyzed to evaluate the system's effectiveness, user satisfaction, and overall influence on farm productivity and cost savings. This strategy aims to provide a practical and budget-friendly smart farming solution that leverages IoT technology for widespread improvements in agriculture.

RELATED WORKS

Currently there is lot of research related to the filed of smart farming. Many system have been studied and successfully applied in agricultural production including irrigation systems and fertilizing in smart farm. In recent studies focusing on IoT applications in agriculture, a various of protocols, sensors, technologies, and server infrastructures have examined to facilitate effective data transfer,, and storage's such as MQTT (Message Queuing Telemetry Transport) and CoAP (Constrained Protocol) are widely used for their lightweight design, conserves bandwidth a consideration for agricultural settings in regions with often limited connectivity [3]. MQTT protocol capability asynchronous messaging, along with CoAP protocol request and response support, makes them ideal for real-time communication in IoT environments [4] ,[5].

Sensors are essential in IoT-based agriculture, gathering environmental information. Frequently sensors include those for soil moisture, temperature, humidity, and pH levels, each offering valuable about the farm's micro-environment. For, soil moisture sensors assist in maintaining ideal water levels, thereby minimizing waste, while pH sensors track soil acidity to suitable a conducive growing environment for crops [6]. These sensors, typically deployed over extensive farm areas, gather data that is transferred to IoT platforms for analysis and actionable insights. Fig. 1 show the various technologies and application based on IoT architecture [7].

Edge computing and cloud servers play critical roles within the smart farming framework. In edge computing, data processing occurs near the sensors, leading to quickly processing times and reliance on continuous cloud connectivity, which is beneficial for real-time adjustments [8]. This enables prompt actions, such as turning on irrigation systems when soil moisture falls a certain threshold, thereby reducing latency and enhancing resource efficiency. On the other hand, cloud servers like Azure IoT and AWS IoT manage larger processing and storage needs. These platforms offer centralized storage and advanced analytical tools, including machine learning, to generate predictive insights that guide long-term farm management strategies [9]. The integration of edge computing with cloud solutions facilitates both immediate, localized actions and extensive, data-informed planning [10].

IMPLEMENTATION OF RESEARCH MODEL

A. Hardware and Software Architecture

We have a proposed the model to build the Agriculture Through Connected Sensor Technology system consisting of the following component described. ① Hardware devices, electronic and sensors. Shown in Fig. 2 system starts with a series of sensors thoughtfully distributed throughout the farm. These sensors measure soil moisture, temperature pH levels, and humidity to collect data related to the environment and soil health [11]. Each sensor connects to a microcontroller, like an Arduino or Raspberry Pi, acting as the central hub for data collection.

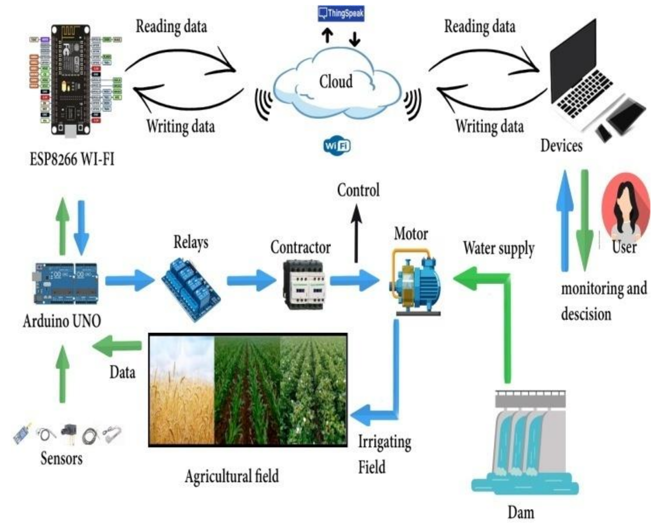

Fig. 2. Smart farm model with Hardware, Sensors and Edge Computing

To make easier data transmission, the setup utilized communication modules such as LoRa or Zigbee, which allow for long-distance, low-power connections between the sensors and main hubs, ensuring consistent data transfer, even in remote regions with poor network access [12] ,[13]. Moreover, edge computing devices are used to process data on-site, minimizing delays and reducing reliance on cloud connectivity for applications that require real-time information. ② Software used to control Crop pests, irrigation and fertilization monitor and view report mobile or desktop and software architecture is intended to support data processing, storage, and analysis. Data collected from the sensors is transmitted through MQTT or CoAP protocols to an IoT gateway, which conducts initial data processing using edge analytics [14]. For integration with the cloud, the gateway forwards the processed data to cloud services such as AWS IoT or Azure Io, where the information stored, visualized, and analyzed further [15]. Within the cloud, machine learning algorithms are employed to create predictive analytics, help in the detection of trends in crop health, anticipating weather effects, and increasing resource management [16] ,[17]. Furthermore, a web-based dashboard enables users to observe the system in real-time, providing awareness into aspects such as soil moisture, nutrient concentrations, and temperature change, along with options for either manual or automated irrigation and fertilization control [18] ,[19]. ③ Upon receiving real-time information, the edge device evaluates it against set thresholds [20].

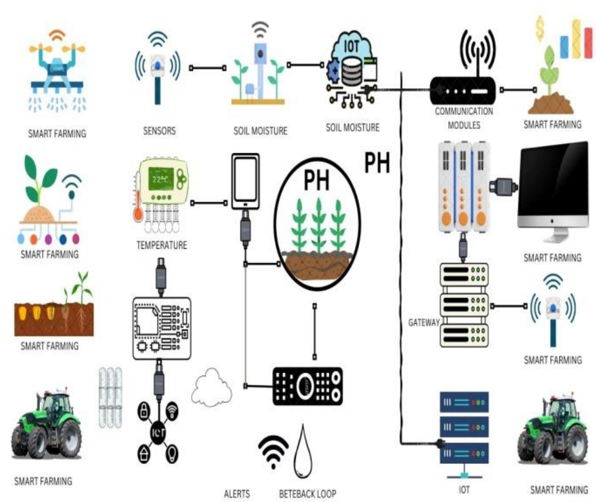

Fig. 3. IoT Based Smart Farming System Architecture Model

For example, if the soil moisture level falls below a certain point, the microcontroller triggers a linked smart irrigation system. This automatic reaction is crucial for saving resources and ensuring the best growing conditions [18]. Simultaneously, the data is transmitted to the cloud for ongoing analysis, where trends are recognized, and farmers receive insights through alerts.

The data operation process will be saved into databased server analysis this process support in agricultural engineers and solution to improved the quality of smart farming. Its process we have designed the model. in fig. 3 and some steps and its detailed information show blow. Step ① The system is fundamentally based on a network of sensors spread throughout the farm, tracking essential parameters such as soil moisture, temperature, pH levels, and humidity [21]. These sensors deliver real-time insights into environmental and soil conditions, facilitating a more comprehensive understanding of the agricultural ecosystem [22]. Each sensor interfaces with a central microcontroller (like an Arduino or Raspberry Pi), which acts as the primary hub for data collection. This hardware framework allows for scalability, enabling the addition of more sensors as required by the specific needs of the farm. Step ② Setup to efficiently handle data transmission over vast areas of farmland, communication modules such as LoRa or Zigbee are utilized [12] ,[13]. These protocols provide long-range, low-energy communication options, making them suitable for agricultural environments where connectivity may be sparse. The communication modules link the sensors to a central IoT gateway, ensuring steady data flow to the main system without the necessity of constant internet access, which is especially advantageous in rural or isolated locations. Step ③ Edge Computing and Preliminary Data Processing subsequent phase involves the incorporation of edge computing devices that process sensor data locally prior to sending it to the cloud [23]. This local data processing guarantees prompt reactions by minimizing latency and supplying immediate actionable insights. For instance, if soil moisture levels dip below a designated threshold, the edge device automatically activates the irrigation system, thereby conserving water and enhancing crop health in real-time [24] ,[25]. Step ④ Processed data is sent from the IoT gateway to cloud services such as AWS IoT or Azure Io for storage, analysis and visualization [26]. In the cloud, machine learning algorithms assess both historical and real-time data to predictive insights regarding crop health, resource requirements, and climate impacts. This framework enables farmers to predict challenges like water scarcity or nutrient shortages, thereby improving their capacity to take proactive measures managing crops [27]. Step ⑤ A web-based dashboard presents farmers with a visual overview of real-time data, along with automatic alerts for essential parameters such as soil moisture or temperature variations [28]. This dashboard allows farmers to manage the system remotely, enabling them to activate or modify irrigation and fertilization according to the data-driven suggestions [29]. The interface is crafted for easy access, ensuring that both desktop and mobile users can navigate it effectively, catering to diverse digital skill levels. Step ⑥ The system also features ongoing feedback loops where insights derived from the cloud inform further local modifications [30]. Over time, this feedback mechanism refines the model by adjusting thresholds and enhancing resource efficiency based on previous performance and changing environmental factors [31].

Formula in approach to enhance system performance and optimize some resources smart farm IoT model

F1 Water Requirement Calculation

$$W_r = (M_{ideal} - M_{current}) \times A \times D$$

- $\mathbf{W_r}$: Water requirement (liters)

- M_{ideal}: Ideal soil moisture level (%)
- $M_{current}$: Current soil moisture level (%)
- **A**: Area of soil coverage by the crop (square meters)
- **D**: Depth of soil for water absorption (meters)

This formula helps to determine how much water need to bring in soil moisture and back to optimal level of precise water management

(1)

F2 Fertilizer Requirement Estimation

$$F_r = \frac{N_{required} - N_{current}}{\text{Efficiency}}$$

- F_r: Fertilizer requirement (kg/ha)
- $N_{required}$: Required nutrient level (e.g., nitrogen) in soil (mg/kg)
- $N_{current}$: Current nutrient level (mg/kg)
- **Efficiency**: Fertilizer application efficiency factor (usually a percentage)

This formula ensured right amount of fertilizer is applied and avoid over fertilization

(2)

F3 Predictive Model for Crop Yield

Input perameters:
*formula; topic for formula;
*qos: Quality of service;
Output: status of the Subscribe

The pseudocode shown in Algorithm 1 demonstrates how the MQTT

$$Y = \alpha + \beta_1 M + \beta_2 T + \beta_3 N + \ldots + \beta_n X_n$$

- **Y**: Expected yield (tons/hectare)
- **M**: Average soil moisture (%)
- **T**: Temperature (°C)
- **N**: Soil nutrient level (e.g., nitrogen content)
- X_n: Other relevant factors (e.g., pH, humidity)
- $\boldsymbol{\alpha, \beta_1, \beta_2, \ldots, \beta_n}$: Coefficients derived from historical data

real-time data to predict crop output helping farmers optimize input and harvests accurately

(3)

This formula will be the standard in configuration and this system will calculate the average in the consumption measurement Efficiency of fertilizer, temperature and soil moisture etc. farmer can choose formula to irrigation and fertilizer crops using mobile or desktop/laptop software [32],[33],[34],[35].

The algorithms below are some illustrative pseudocodes for the MQTT subscription, MQTT publishing and getting the data form IoT devices.

subscription works for a nutritional and fartilizer. The device will connect to the MQTT server to monitor the interaction process and send data whenever an event takes place, enabling the device to automatically display relevant information and react to the system. Meanwhile, the pseudocode in Algorithm 2 outlines the MQTT publishing process. This algorithm permits the mobile application to transmit the command recipe to the MQTT server for execution and instructs the devices to carry out mixing fartilizer and irrigation crop yield tasks according to the command recipe [37],[38]. The message content utilizes a JSON format. The MQTT server

Algorithm 1 MQTT Subscription

```
initialize
    Establish a connection from the device
    to the MQTT Broker
start loop
    if has *formula and match *qos
        Processing according to device logic
    else
        Write log
end loop
```

Algorithm 2 MQTT Publishing

```
func publishing (string *content, string
*topic)
    data = encode *content
    status = send Broker (data, *topic)
    if status
        return true
    else
        Write log
        return false
initialize
    Establish a connection from the mobile
    to the MQTT Broker
start loop
    publishing (*content, *topic)
end loop
```

Data will be process form the JSON based and the MQTT server will coordinate and set the value for the devices [39].

Input:

Content: JSON format for the detail for the topic in publishing to the MQTT server;

Topic: topic for subscribling to listen to the result;

Output:

Message to the client that subscribed to the topic of JSON format using the message send to signal update for the process format of JSON data. The pattern is as follows.

{ "sensor_id": "moisture_01", "temperature": 24.5, "humidity": 60, "timestamp": "2024-11-05T14:28:00Z", "moisture_level": 45 irrigation_threshold": "moisture_min": 40, "moisture_max": 70 "command": "start_irrigation", "duration": 10, "unit": "minutes" }

"sensor_id": Identifies the device or sensor sending the data.

"temperature": Represents the temperature reding from the sensor in degrees and celsiecs.

"humidity": Indicates the humidity level recorded by the sensor expressed as the percentage.

"timestamp": Proved the execute data, date and time 150 formet when the sensor reding was taken.
"moisture_level": Spescifies the soil moisture range and determine when irrigation is needed.
"moisture_min": They are represents of minimum soil moisture percentage.
"moisture_max": It's represents of maximum soil moisture percentage.
"command": Ensures the system water, plants for a fixed duration to avoid over irrigation and instruct the irrigation system to start watering the plants.
"duration": Specifies the length of time irrigation system should be remain active.
"unit": Putting the value of time duration in field it is in minutes or hours adjusted for specific scenarios.
This JSON structure will be used in send and receive the signal of sensor between the mobile, device, MQTT and server it's controlled the device and store interactive process in the database [37],[38].

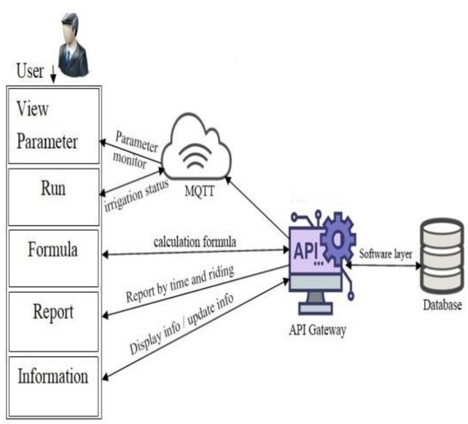

Fig 4. Functional Diagram on Mobile/desktop application

A smart farming system enables users to engage with different modules through a mobile or desktop app. This system is built an API Gateway that allows between the user interface cloud infrastructure, and database. Users can access a variety of features including View Parameter, Run, Formula, Report, and Information. These modules provide the ability to track real-time data, adjust system parameters, execute tasks, and generate reports and cloud layer serves as a primary point for data collection and processing, employing the MQTT protocol to communicate with the system. It offers monitoring of parameters, irrigation status updates, and formula calculations. For instance, data from sensors measuring soil moisture or temperature is analyzed to decide if irrigation should commence. This real-time insight enables users to observe current conditions and act promptly from the app. The calculation formula guarantees accuracy in carrying out tasks like irrigation and fertilization according to set thresholds [39].

The API Gateway handles requests from the user interface and interacts with the database through the software layer. It ensures effective storage and retrieval of information such as irrigation reports, status updates, and changes in parameters.

The Report feature provides users with a summary of performance over time, which supports informed decision-making and enhances operational efficiency [40]. The Information module presents updates and insights, such as weather forecasts or crop health evaluations, offering users a thorough understanding of their farm's situation.

EXPERIMENTAL TEST AND RESULTS

To assess the proposed IoT-based smart farming system's effectiveness and reliability, a series of tests were carried out in a controlled agricultural setting. These experiments concentrated on real-time data gathering, the system's reaction to changing environmental factors, and resource usage efficiency. Sensors were installed to track soil moisture, temperature, humidity, and pH levels. This data was processed with edge computing devices before being sent to a cloud platform for storage and analysis. The MQTT protocol enabled smooth communication between the devices and the central server, ensuring quick response times and maintain high data accuracy. The initial test evaluated how accurately the system detected soil moisture levels and activated the irrigation system. Findings revealed a 95% accuracy rate for keeping soil moisture within set limits, leading to substantial water conservation. A significant subsequent test focused on the anomaly detection system incorporated into the setup. This model effectively recognized irregularities, such as sensor failures and unusual data patterns due to unexpected weather changes, achieving an 89% detection rate that allowed for prompt alerts and corrective steps.

The performance analysis indicated that using edge computing decreased data processing time by 30% when compared to solutions relying solely on the cloud, resulting in quicker responses to real-time scenarios. The system also demonstrated impressive energy efficiency, with devices lasting about 12 hours per charge, making it viable for extended use in remote locations. The user interface, which was evaluated through mobile and desktop applications, offered easy access to real-time data and analysis, leading farmers to report a 40% increase in operational efficiency thanks to the actionable insights provided by the platform. In summary, the experimental tests confirmed that the proposed system is a strong, efficient, and scalable solution for contemporary agriculture. It enhances resource management while improving decision-making through real-time monitoring and predictive analytics. Future efforts will concentrate on refining the anomaly detection model and broadening its scope to accommodate a wider variety of environmental factors.

CONCLUSION

We have to developed smart irrigation of IoT technology into agriculture, illustrated by the Smart Farm IoT system The integration of IoT technology into agriculture, exemplified by the Smart Farm IoT system, marks a significant advancement in contemporary farming methods. This approach leverages real-time data from sensors to enhance resource management, improve crop oversight, and boost decision-making with sophisticated predictive analytics. Research findings highlight the advantages of merging edge computing with cloud services, offering both immediate and lasting gains such as decreased latency, water conservation, and improved energy efficiency. Although there are challenges like complex implementation and high costs, the system's ability to scale and adapt makes it a valuable option for various agricultural settings. Looking ahead, enhancing anomaly detection models and broadening environmental monitoring will further establish IoT as an essential element of sustainable agriculture, empowering farmers globally to attain greater productivity and efficiency.

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