UTILIZATION OF IOT IN AGRICULTURE FOR SMART CROP MONITORING

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Abstract:
Agriculture, being one of the most critical sectors for global food security, is undergoing a transformation through the adoption of Internet of Things (IoT) technology. Traditional farming methods, which rely heavily on manual observation and uniform treatment of crops, often result in inefficient resource use and inconsistent yields. This paper proposes an IoT-based sensor network to establish a smart crop monitoring system that collects real-time data on key agricultural parameters. These sensors are integrated with microcontrollers and wireless communication modules, which transmit the data to a cloud platform for storage and analysis. The goal of the system is to empower farmers to make informed, data- driven decisions by detecting early signs of stress in crops and enabling timely interventions such as precision irrigation and pest control. By automating the processes of data collection and interpretation, the system not only reduces manual labor but also improves the accuracy and efficiency of field operations. The proposed solution was tested in a real-world agricultural environment, where it demonstrated a significant improvement in water-use efficiency— reducing irrigation volumes by over 20%— and enabled early detection of environmental stress factors.

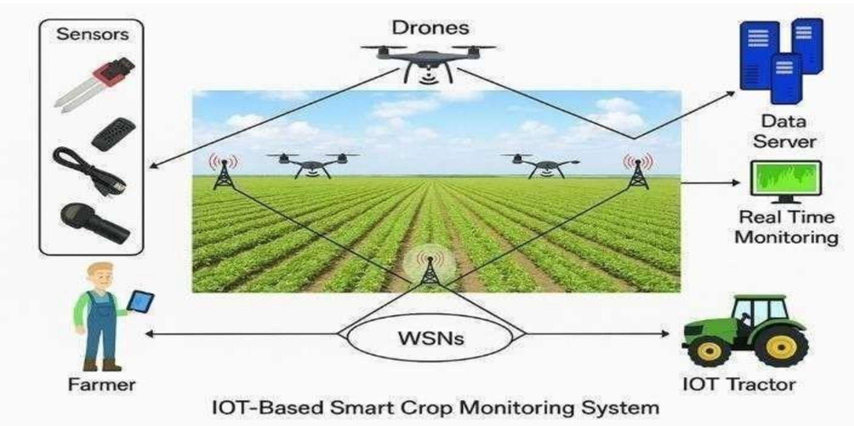
Keywords: Sustainability, Smart Agriculture, Internet of Things (IoT), On-Farm Water Management, Food Security, SDG.

1. INTRODUCTION

Agriculture remains one of the world's most essential sectors for human survival, economic growth, and the sustainable use of natural resources. With the global population projected to exceed 9.7 billion by 2050, agriculture must evolve to meet growing demands for food, fiber, and fuel without compromising environmental sustainability [1]. This challenge is compounded by the adverse effects of climate change, including irregular rainfall, droughts, and increasing poverty that impact both local farm production and global food security. Traditional farming methods, although effective in the past, are now insufficient to handle these modern complexities. They often involve generalized treatment of large areas of land and lack the ability to provide timely feedback based on changing environmental conditions. This results in inefficient water usage, overuse of fertilizers and pesticides, poor pest and disease management, and ultimately, reduced crop yields [2]. The adoption of Internet of Things (IoT) technology—commonly known as "smart agriculture" or "precision agriculture"—offers a more effective and sustainable alternative. IoT refers to a network of internet-connected devices and sensors that collect and transmit real-time data from the farm. These systems can be either standalone or remotely operated, and they monitor critical parameters like soil moisture, temperature, humidity, light intensity, and overall crop health [3]. IoT-enabled sensors send data wirelessly to cloud servers or centralized locations where advanced analytics and visualization tools transform raw data into actionable insights. For example, when soil moisture drops below a set threshold, the system can automatically trigger irrigation, conserve water and avoid unnecessary usage [4]. Currently, IoT is driving a major shift from reactive to proactive and predictive farming. Farmers no longer need to rely on visual inspections or fixed calendar schedules. Instead, they can make real time decisions based on accurate field conditions and predictive forecasts. This enables improved crop growth, higher yields, reduced input costs, and minimized environmental impact [5]. Furthermore, IoT facilitates agricultural automation. For instance, smart irrigation systems can operate autonomously based on real-time soil moisture and weather data. Predictive analytics can alert farmers to potential pest or disease outbreaks in advance, allowing them to take timely preventive measures. IoT also serves as the foundation for scalable, data driven farming systems integrated with satellite remote sensing, GPS, and artificial intelligence—empowering farmers to manage varying field conditions efficiently and sustainably.

2. LITERATURE REVIEW

The application of Internet of Things (IoT) technology in agriculture is transforming the way farming is regulated and monitored by providing real-time information about environmental conditions and crop health. Numerous studies have emphasized how smart technologies enhance precision, efficiency, and sustainability in agricultural practices. One of the most significant uses of IoT is in environmental monitoring. Smart sensors are used to track soil and climatic conditions such as moisture levels, temperature, humidity, and total dissolved solids. In a recent study, Qamar et al. [1] investigated the effectiveness of IoT-based sensors during the early growth stages of crops. Their findings showed that real time data collection helped in timely irrigation, efficient water usage, and improved field management. The study concluded that sensor-based monitoring reduces human error, enhances soil health, and increases crop yield. Similarly, remote sensing technologies are being increasingly employed in agriculture. Tsetkova et al. [2] used high-resolution aerial and satellite imagery to assess the health of pepper crops. Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), were used to monitor plant stress levels, which helped improve the timing and effectiveness of interventions. When combined with IoT-based ground sensors, NDVI provides a dual-layered monitoring system that significantly improves crop health management. Wireless communication protocols such as LoRa, Zigbee, and Wi-Fi are essential for transmitting sensor data across large farming areas. Bacco et al.[4] explained how these low-power wireless technologies enable efficient and scalable deployment of sensor networks in rural areas. These networks, when integrated with cloud platforms, allow for continuous data analysis, historical trend monitoring, and real-time visualization through user-friendly interfaces. Intelligent irrigation systems have also shown significant advantages. Wasswa et al. [5] demonstrated how automating irrigation using real-time soil moisture data and remote control can conserve water, reduce wastage, and prevent over- irrigation. Their research also showed that predictive models and weather forecasts can further optimize irrigation planning, supporting sustainable water management practices. Despite these advantages, large-scale adoption of IoT in agriculture faces several challenges. One of the primary barriers is the high initial cost of sensors and infrastructure, particularly for small or resource-limited farmers. Another major constraint is limited digital literacy among end users, which hinders their ability to effectively use data-driven systems. To address this, Patel et al. [6] developed simplified sensor platforms integrated with mobile applications and graphical dashboards, making it easier for farmers to interpret field data and make informed decisions. Swarnkar et al. [3] also pointed out that issues such as sensor calibration errors or unstable network connectivity can affect the accuracy of real-time alerts. They recommended hybrid monitoring systems that combine satellite imagery, historical data, and sensor validation algorithms to create more robust and reliable decision-making frameworks.



Modern agriculture is being revolutionized by technological interventions, particularly through the adoption of the Internet of Things (IoT). These advancements have transformed how crops are monitored, maintained, and optimized. Among the most impactful technologies is IoT, which enables real-time monitoring, analysis, and control of various agricultural processes. An IoT-based intelligent crop monitoring system typically integrates sensors, wireless networks, drones, servers, and automated machinery into a unified ecosystem, supporting farmers in making informed, data-driven decisions.

➢ **Sensors:**

The Foundation of Data Collection Sensors are critical for continuously monitoring environmental and agricultural conditions. They are deployed across different areas of the farm to collect key data.

- Soil Moisture Sensors: Measure the water content in the soil, helping farmers determine the timing and amount of irrigation needed [1]. · Soil pH and Nutrient

Sensors: Assess soil acidity and nutrient levels, which guide fertilizer application. These sensors transmit real-time data to nearby processing units or remote servers using wireless communication protocols. They are usually powered by solar panels or long-lasting batteries, making them suitable for remote locations. Their accuracy and continuous monitoring capabilities help detect early signs of crop stress, enabling timely intervention. Moreover, by monitoring different farm zones, they support site-specific crop management—a core principle of precision agriculture.

➢ **Wireless Sensor Networks (WSNs):**

Data Connectivity Backbone Wireless Sensor Networks (WSNs) ensure seamless data transmission across large farms. A WSN consists of multiple sensor nodes equipped with microcontrollers, power sources, and communication modules. Data is transmitted either directly to a central gateway or through multi-hop routing, where it passes from node to node until it reaches the main receiver. Communication technologies such as Zigbee, LoRa (Long Range), NB-IoT, and Wi-Fi are used depending on the farm size and energy requirements. LoRa, for example, enables long range communication—up to 15 kilometers in rural areas—with minimal power usage, making it ideal for farms lacking grid electricity [2]. WSNs are designed to minimize data loss and maintain performance under variable field conditions. These networks are also self-healing, meaning that if one node fails, data can be rerouted through alternate paths. This reliability forms the foundation of modern agricultural IoT platforms, ensuring continuous connectivity between the field and the cloud.

➢ **Drones (UAVs): Aerial Monitoring and Surveillance**

Unmanned Aerial Vehicles (UAVs), or drones, provide a valuable aerial perspective in smart farming. Unlike stationary sensors, drones can capture high-resolution spatial data over large areas. They are equipped with multispectral and hyperspectral cameras, thermal sensors, and GPS systems. Drones collect data on:Crop health (using indices like NDVI), Irrigation patterns and pest hotspots, Soil variability and crop density. By flying pre-defined routes, drones gather spatial information efficiently and with greater detail than ground-based sensors. This enables detection of micro-level issues that may not be visible to the naked eye or traditional tools [3].

➢ **IoT-Enabled Tractors and Farm Machinery**

Modern agricultural machinery—such as tractors, seeders, and sprayers—are increasingly equipped with IoT modules, GPS, and AI-based controllers. These intelligent machines can be remotely operated or run autonomously based on data from the monitoring system. For example, a tractor can be programmed to fertilize only specific sections of the field identified by sensors as nutrient-deficient, without human input [5]. This automation reduces labour, minimizes errors, conserves fuel and other resources, and lowers the environmental impact of farming operations. Related Work and Literature Synthesis IoT- based smart agricultural technologies have advanced rapidly in recent years. Various studies demonstrate the effectiveness of integrating wireless sensors, remote sensing tools, and AI-based analytics to monitor crop health, manage irrigation, and optimize resource use. Kumar et al. [1] developed a basic IoT system using soil moisture, temperature, and smoke sensors on an Arduino platform. Their system included threshold-based irrigation, a fire alert mechanism, and data communication via NRF24L01 modules connected to a

Raspberry Pi. This low-cost system enabled automated decision-making based on pre-set thresholds. Suma et al. [2] designed a sensor array to measure soil temperature and water content,integrating a GSM module for real-time alerts. Their system featured both manual and automatic modes, giving farmers the flexibility to switch between user control and sensor driven automation. Beyond standalone systems, large-scale weather monitoring networks have been implemented commercially. For instance, in the U.S., extensive weather stations have been deployed in apple and lettuce fields. These networks use GIS and GPS-based mapping tools to assess pest risks, optimize irrigation, and support real-time decision-making across vast areas [3]. These examples reflect how the integration of IoT with other advanced technologies can significantly improve agricultural productivity, resource efficiency, and decision-making capabilities.

Table1-SOIL MOISTURE SENSOR SPECIFICATION

Parameter	**Specification**
Sensing Range	0–100%Volumet ric Water Content (VWC)
Resolution	0.001m³/m³
Accuracy (Calibrated)	±0.03 m³/m³
Design Type	Low- power digital sensor
Data Sampling Interval	Default:2 0 minutes; Minimum :1 min
Transmission Mode	Aligned with sampling frequency

Table2-WEATHER TRACKER

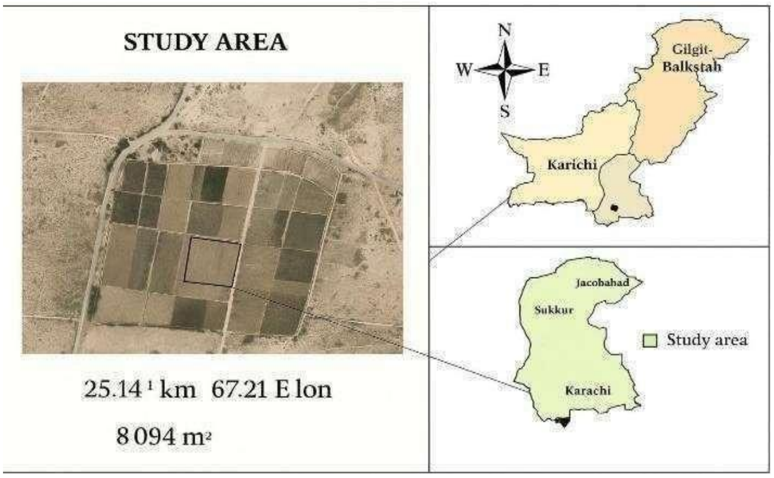
Measurement Parameter	**Specification**
Temperature Range	-20to 65°C
Temperature Accuracy	±1.1°C
Temperature Resolution	0.1°C
Humidity Measurement	10to99%RH
Humidity Accuracy	±5%
Humidity Resolution	1%
Rainfall Accuracy	±10%
Rainfall Resolution	0.254mm (0.01inch)
Solar Radiation Range	0 to200,000Lux
Solar Radiation Resolution	1 Lux

Remote sensing has significantly enhanced agricultural monitoring by enabling crop observation through satellite imagery. For example, in Uzbekistan, satellite data has been used to analyse geospatial patterns in cotton growth, forecast yields, and identify soil salinity. These technologies complement ground-based sensors by providing broader spatial coverage, which is especially useful in areas where physical sensor deployment is limited [4]. The integration of Geographic Information Systems (GIS) with aerial multispectral imaging has further improved the precision of disease and pest detection in smart farming. A notable example is from Washington State, where aerial NDVI imagery was combined with trap-based pest surveys for apple orchards. This integration of IoT, geospatial tools, and biological data enabled a comprehensive crop risk analysis framework [5]. Another area of rapid advancement is the use of

Decision Support Systems (DSS) in IoT-based agriculture. These systems combine data from ground sensors, drone imagery, and artificial intelligence (AI)-based analytics into unified platforms. Research has shown that such integrated systems can reduce water waste and create accurate irrigation schedules aligned with the goals of Sustainable Development (SDG) for agricultural productivity and resource efficiency [6]. Smart irrigation systems, often enhanced with AI, are now central tools in modern agriculture. They forecast water requirements and ensure efficient usage [7]. Similarly, sensor-based systems are being integrated with machine learning algorithms to allow adaptive fertilization and targeted crop diagnostics [8]. Geospatial technologies are also gaining traction in arboriculture and other agricultural sub-sectors to support resource management and sustainability goals [9]. Overall, literature consistently supports a shift from conventional to data-driven farming. When IoT is combined with AI, GIS, and wireless communication, farmers are empowered to make informed decisions, reduce labour dependency, and maximize yields. This integration represents a move toward autonomous, responsive, and scalable agricultural ecosystems of the future. VI. Sensor specifications and Experimental Setup To evaluate environmental and soil conditions during the early stages of crop development, a smart weather monitoring and soil moisture sensor system was installed on a tomato farm. The monitoring period spanned from November 1st to December 5th, 2022, which coincided with the crop's initial growth phase. The system continuously recorded data on temperature, humidity, rainfall, solar radiation, and volumetric soil water content. This allowed for intensive real-time field monitoring with minimal human intervention. The goal was to enhance water management, optimize irrigation scheduling, and improve resource conservation. These efforts contributed to promoting sustainable agricultural practices by increasing water-use efficiency, preserving soil structure, and boosting yield potential.

3. STUDY AREA DESCRIPTION

The experimental study was conducted in Gadap Town, located approximately 15 kilometers northeast of Karachi, in the Sindh Province of Pakistan. The geographical coordinates of the site are 25.14°N latitude and 67.21°E longitude, and it spans an area of 8,094 square meters. This site was selected because of its agricultural relevance in the region and its suitability for implementing IoT-based smart farming technologies. The region's environmental conditions and farming practices provided an ideal testing ground for evaluating the impact of smart agriculture tools on crop productivity and resource optimization.



The Sindh province has a total area of approximately 140,900 square kilometers, of which around 48,700 square kilometers is arable land. It is recognized as a key agricultural region in Pakistan, second only to Punjab in overall agricultural production. Sindh's climate is primarily classified as arid to semi- arid, owing to its subtropical geographical location. The region receives most of its annual rainfall during the Southwest Monsoon season (July to September), with average rainfall ranging from 150 to 250 millimeters. Occasionally, it also receives light winter rainfall due to weak western disturbances. The major cropping systems in Sindh include rice–wheat and cotton farming, which are central to the province's agricultural economy.

4. METHODOLOGY

To analyze the performance of a low-power, IoT based crop monitoring system, a pilot agricultural experiment was conducted for tomato farming in Gadap Town, located in the Sindh Province of Pakistan. The primary objective was to evaluate the cost-effectiveness and feasibility of using low-power sensor-based systems for real-time monitoring of soil and weather conditions.

System Components and Configuration

The experimental setup consisted of:

- Capacitive soil moisture sensors – used to measure volumetric water content in the soil.
- DHT11 sensors – used to detect ambient temperature and humidity levels. These sensors were selected based on factors such as low cost, reliability, and compatibility with IoT microcontroller units. The system was specifically designed to support real- time monitoring in a cost-efficient manner for small-scale farming applications.

Soil Moisture and Temperature Thresholds

The system was programmed with the following threshold values:

- Soil moisture: An alert was triggered when volumetric water content (VWC) dropped below 25%.
- Temperature: An alert was activated when the ambient temperature exceeded 35°C. Once these thresholds were crossed, the system automatically sent SMS alerts to the farm manager. These alerts enabled timely interventions, such as starting irrigation, and helped prevent water wastage and potential crop damage.

Data Collection Frequency

The sensors were configured to collect data every 15 minutes to ensure sufficient resolution for detecting short-term environmental changes. All data samples were time- stamped and synchronized with a cloud server for real-time access, analysis, and decision-making support. The core objective of deploying this system was to:

- Enhance water-use efficiency,
- Minimize labour requirements for field monitoring and irrigation,
- Enable precision agriculture through data-driven decisions. The results of this deployment aligned with the findings of Qamar et al. [1], who demonstrated similar improvements in decision- making and water resource management using IoT-based environmental sensors in tomato farming under semi-arid conditions.

5. RESULTS

The IoT-based smart crop monitoring system was deployed and tested over a continuous 30-day period during the early growth phase of tomato plants. The system successfully demonstrated its potential in optimizing water usage, improving responsiveness to environmental changes, and enhancing data analysis for strategic crop management.

➢ **Reduction in Water Consumption**

The most significant outcome of the pilot deployment was a 25% reduction in irrigation water usage compared to traditional manual irrigation methods. This efficiency was achieved primarily through real-time monitoring of soil moisture levels, allowing irrigation to occur only when and where needed, based on predefined moisture thresholds. Unlike traditional time-based irrigation systems, the sensor-based solution delivered water precisely when the soil exhibited moisture deficiency. This aligns with similar findings in previous studies, which also reported water savings through sensor assisted automated irrigation in tomato cultivation.

➢ **Early Detection of Environmental Stress**

Another key observation was the system's ability to detect temperature anomalies that could indicate potential pest infestations— approximately three days earlier than manual inspection methods. When the outside temperature exceeded the preset threshold of 35°C, the DHT11 temperature sensor triggered an automatic alert via the Things Board platform, notifying the farm manager in real time. This early warning system enabled timely field inspections and proactive pest control, reducing crop damage and minimizing the unnecessary use of pesticides.

- **Operational Efficiency and Scalability**

In addition to environmental benefits, the system significantly reduced labour requirements for field monitoring and irrigation. Thanks to wireless communication and automated alert generation, farm managers no longer needed to make frequent on-site visits to check environmental conditions. This greatly enhanced operational efficiency and made the solution highly scalable for use in larger agricultural fields. Furthermore, the use of cost-effective components—such as the ESP32 microcontroller, capacitive soil moisture sensors, and the DHT11 module—ensures affordability. When combined with open-source platforms like Things Board, this system offers a low-cost entry point into digital farming, making it especially valuable for resource- constrained region

6. CONCLUSION

This study highlights the transformative impact of Internet of Things (IoT) technology on modern agriculture. By deploying flexible sensors capable of monitoring real-time weather and soil conditions, farmers are no longer limited to manual observation or guesswork. Instead, they gain access to accurate, data-driven insights that support informed decisions in areas such as irrigation, fertilization, and overall crop management. Field implementation— particularly in tomato cultivation—showed that real- time monitoring of soil moisture, temperature, and environmental data led to optimized irrigation scheduling. This approach ensures the efficient use of water resources and eliminates the inefficiencies of traditional irrigation methods, which often lead to overwatering and resource waste. Remote sensing of field conditions further improved timeliness and convenience, contributing to better yield and higher crop quality. Beyond short-term benefits, the study also opens up exciting future possibilities. Integrating IoT with Artificial Intelligence (AI) and Geospatial Analysis can enable predictive apabilities—such as forecasting crop stress, climate change effects, and pest outbreaks. This would further enhance input efficiency and support long-term farm sustainability.

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