Scalable Cloud-Edge AI Framework for Precision Irrigation and Crop Health Monitoring using IOT Data Streams

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Abstract: Precision agriculture requires timely insights derived from heterogeneous sensor data to improve irrigation efficiency and maintain crop health. Traditional centralized monitoring systems often suffer from high latency, limited scalability, and delayed decision-making when handling continuous agricultural data streams.This paper presents the design and implementation of a scalable cloud–edge integrated framework for real-time agricultural monitoring. The proposed system combines IoT-based sensor data collection at the field level with cloud-based stream processing and analytics to enable continuous monitoring of environmental parameters such as temperature, humidity, soil moisture, light intensity, pH, and nutrient levels. A distributed ingestion pipeline using MQTT and Apache Kafka ensures reliable and scalable data transmission, while real-time stream processing enables dynamic alert generation and decision support for irrigation and crop health assessment. Historical data is stored in a time-series format to support trend analysis and visualization.Experimental evaluation using a simulated agricultural environment demonstrates the system's ability to process sensor data in real time, detect abnormal conditions, and provide actionable recommendations. The results highlight the effectiveness of cloud–edge integration in supporting precision irrigation and proactive crop health management.
Keywords: **Precision Agriculture; Internet of Things (IoT); Cloud–Edge Computing; Real-Time Data Analytics; Smart Irrigation**

Introduction

Agriculture is increasingly dependent on data-driven decision-making to address challenges such as water scarcity, climate variability, and declining soil health. Traditional irrigation and crop monitoring practices often rely on manual inspection and periodic sampling, which are insufficient for capturing rapid environmental changes in modern farming systems.

Recent advancements in the Internet of Things (IoT) and cloud computing have enabled continuous monitoring of agricultural parameters such as soil moisture, temperature, humidity, nutrient content, and crop condition. However, many existing systems struggle with scalability, latency, and effective real-time decision support when deployed over large agricultural fields.

This work addresses the problem of designing and implementing a scalable cloud–edge integrated framework capable of real-time data collection, processing, alert generation, and decision-making for precision irrigation and crop health monitoring. The proposed framework aims to provide timely alerts, persistent monitoring of abnormal conditions, and actionable recommendations using continuous IoT data streams.

Related work

The journey toward smart, connected farms has been marked by a steady evolution in how we architect IoT systems, moving the "intelligence" of the system closer and closer to the field itself.

Early foundational work proved the concept of automation in agriculture. Systems like the one developed by Gutiérrez et al. [4] successfully used wireless sensor networks to monitor soil conditions and automatically trigger irrigation. This was a crucial first step, showing that real-time data could directly control physical processes. However, these systems were often self-contained; their logic was localized, and they lacked the seamless connection to the powerful, large-scale data processing capabilities of the cloud.

To harness that power, the research community pivoted toward cloud-centric models. Comprehensive surveys, such as the one by Botta et al. [2], mapped out the blueprint for integrating vast numbers of IoT devices with cloud platforms. In this model, every sensor reading travels to a central cloud server, where it is stored, analyzed, and turned into insights on a dashboard. This unlocked unprecedented scalability and complex analytics. Yet, for applications like irrigation where a leaking pipe needs an immediate shutdown, sending data thousands of miles for a simple decision introduced frustrating delays and consumed significant bandwidth—a challenge also observed in broader industrial IoT [5].

This realization sparked the next architectural shift: the move toward edge computing. Researchers like Shi et al. [1] gave a name and a clear vision to this paradigm, arguing for a distributed "cloud-edge continuum." The idea was elegant: handle urgent, simple decisions right where the data is born—at the edge of the network—and only send summarized, valuable data to the cloud for long-term trend analysis and model training. This hybrid approach, supported by the vision of computing as a scalable utility [3], offered the best of both worlds: the low-latency response of localized systems and the boundless analytical power of the cloud.

Today, this cloud-edge hybrid model is the established framework. However, a gap often remains in how fully we exploit the "intelligence" at the edge. In many current agricultural systems, the edge device acts merely as a data forwarder or a simple filter, with most decision logic still residing in the cloud. Our work builds directly upon this established architecture but seeks to push the boundary further. We explore how to embed more sophisticated, multi-parameter, and persistent decision-making directly at the edge, creating a system that is not just responsive, but resilient and intelligently autonomous, even when the connection to the cloud is temporarily lost.
Parameter Key:

- **Cloud-Based Processing:** Utilizes centralized cloud resources for data aggregation, storage, or advanced analytics.
- **Edge/Local Processing:** Incorporates computation or logical decision-making at devices physically or logically closer to the sensors than the cloud.
- **Integrated Agri. Case Study:** Presents a full implementation and evaluation within a specific agricultural application context (e.g., irrigation, monitoring).

Table 1. Compares this work with the related work or previous research by other researchers

	Cloud-Based Processing	Edge/Local Processing	Integrated Agri. Case Study
[4]	No	Yes	Yes
[2]	Yes	No	No
[1]	Yes	Yes	No
This work	Yes	Yes	Yes

Key Contribution

This work contributes to the existing body of research on smart and precision agriculture by presenting a realistic, end-to-end real-time agriculture monitoring framework that bridges the gap between theoretical IoT models and deplorably systems.

The key contributions of this paper are summarized as follows:

1.Realistic sensor-driven alert generation:

Unlike many existing studies that rely on static or synthetic alerts, this system generates alerts strictly based on real-time sensor values crossing scientifically defined thresholds. Alerts are created and resolved dynamically, closely resembling real agricultural field conditions.

2.Alert-derived crop health assessment:

Crop health status is not treated as an independent metric. Instead, it is derived directly from the active alert state, ensuring transparency and explainability. This approach enables farmers and researchers to clearly understand how environmental stress translates into crop health degradation.

3.Stress-mode based experimental framework:

The system introduces a controllable stress-mode mechanism that simulates realistic drought and heat stress conditions by altering sensor value ranges rather than injecting artificial events. This allows repeatable experiments and reliable validation of alert behavior.

4.Explainable and lightweight system design:

The proposed architecture avoids complex black-box models and cloud dependencies. Each decision—alert triggering, severity classification, and recovery—is rule-based and explainable, making the system suitable for academic evaluation, rural deployment, and viva examinations.

5.Research-ready historical data generation:

The system continuously logs time-series sensor data and alert lifestyles in structured CSV and JSON formats. This data can be directly used for further analysis, visualization, or machine learning research without additional prepossessing.

Method, Experiments and Results

The proposed system follows a layered architecture consisting of sensor simulation, data ingestion, stream processing, storage, and visualization layers. Environmental sensors such as soil moisture, temperature, and humidity generate numeric values at fixed time intervals. These values are transmitted through a messaging pipeline and processed in real time.Alert generation is performed using threshold-based rules derived from standard agronomic practices. When a sensor value crosses its defined threshold, an alert is generated with an associated severity level (WARNING or CRITICAL) and a contextual recommendation. Alerts remain active until the sensor value returns to a safe operating range, at which point the alert is automatically resolved.Crop health status is computed dynamically based on the presence and severity of active alerts. A CRITICAL alert marks the crop as Critical, a WARNING alert marks it as Stressed, and the absence of alerts indicates a Healthy crop state.

Experimental Setup

To evaluate the system, controlled experiments were conducted using two operating modes:

•Normal Mode:

Sensors emit values within healthy agricultural ranges, representing optimal environmental conditions.

•Stress Mode:

Environmental stress is simulated by reducing soil moisture levels and increasing temperature values to represent drought and heat stress scenarios.

The stress mode is toggled externally, allowing the system to observe both the onset and recovery phases of environmental stress. All experiments were conducted over continuous time windows to capture alert persistence and resolution behavior.

Results

Figure 1 illustrates the time-series behavior of soil moisture, temperature, and humidity during stress and recovery phases. A sharp decline in soil moisture and a corresponding rise in temperature are observed during stress mode, which results in the activation of multiple alerts.

mThe results demonstrate that:

- Alerts are triggered precisely when thresholds are crossed, without false positives.
- Alert resolution occurs only after sustained recovery of sensor values.
- Crop health status transitions accurately reflect environmental conditions in real time.
- Historical charts clearly capture environmental trends, making stress periods visually distinguishable.

These observations confirm that the system behaves consistently under dynamic conditions and provides reliable insights for agricultural decision-making.

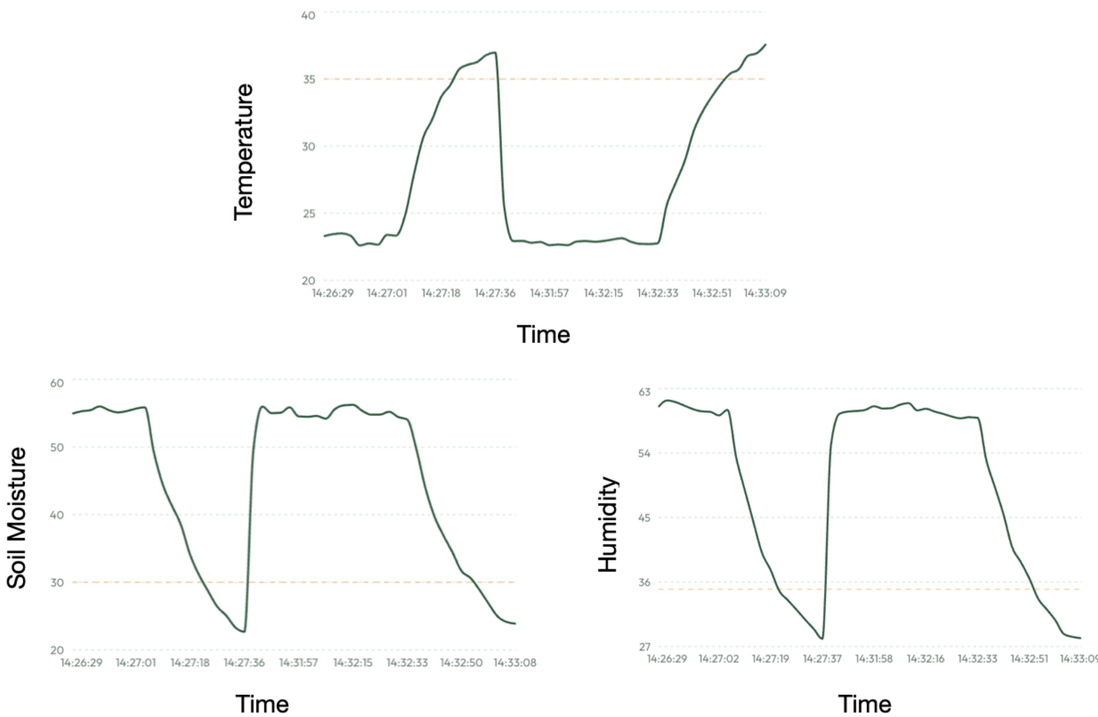

Figure 1. Time-series variation of temperature, soil moisture, and humidity recorded by the proposed IoT-based agricultural monitoring system.

Discussions

The experimental results obtained from the proposed cloud–edge integrated IoT framework demonstrate its ability to capture, process, and analyze agricultural sensor data in real time. The time-series plots of temperature, soil moisture, and humidity (Figure 1) clearly show both stable environmental conditions and stress scenarios, validating the effectiveness of the sensing and data processing pipeline.

During stress conditions, a noticeable rise in temperature accompanied by a decline in soil moisture and humidity was observed. Such correlated behavior reflects real agricultural field conditions, where prolonged heat often leads to moisture depletion and increased evapotranspiration. The system successfully identified these variations and generated alerts based on predefined agronomic thresholds, enabling timely decision-making.

The persistence of alerts until sensor values returned to safe ranges proved useful in avoiding false positives and ensuring that corrective actions were sustained rather than momentary. Additionally, the integration of historical analysis provided insights into environmental trends, allowing farmers or system operators to understand gradual changes rather than relying solely on instantaneous readings.

Overall, the results indicate that combining real-time monitoring with historical trend analysis enhances situational awareness and supports more informed irrigation and crop management decisions. While the system operates in a simulated environment, the observed behavior closely mirrors real-world agricultural dynamics, reinforcing the practicality of the proposed framework.

Conclusions

This work focused on the design and implementation of a scalable cloud–edge integrated framework for real-time agricultural monitoring and decision support. The following conclusions can be drawn:

• Problem Statement Addressed / Motivation: The study addressed the need for continuous, real-time monitoring of environmental parameters to support precision irrigation and crop health management, especially in scenarios where delayed decisions can lead to reduced yield or crop stress.

• Method Used: An IoT-based architecture was developed that integrates sensor simulation, real-time data ingestion, stream processing, alert generation, and historical analysis within a cloud–edge framework. Threshold-based logic was used to derive alerts and crop health status from sensor readings.

• Key Findings: The system effectively captured realistic variations in temperature, soil moisture, and humidity, identified stress conditions, and generated meaningful alerts. Historical time-series analysis provided additional context for understanding environmental trends, improving decision-making beyond instantaneous observations.

• Limitations and Future Work: The current implementation relies on simulated sensor data rather than physical field deployments. Future work will focus on integrating real sensor hardware, incorporating machine learning models for predictive analytics, and extending the framework to support adaptive irrigation control and larger multi-field deployments.

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