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ORIGINAL

Intelligent Monitoring and Early Warning System Against Frosts for Sustainable Agriculture

Sistema Inteligente de Monitoreo y Alerta temprana contra Heladas para una Agricultura Sostenible

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ABSTRACT

Frosts are an adverse climatic phenomenon that severely affects agriculture, causing irreversible damage to plants. This process leads to dehydration, deterioration of plant tissue, and, in extreme cases, total crop loss. The lack of effective prevention and response strategies exacerbates its consequences, resulting in significant economic losses, particularly among small-scale farmers. In Ecuador, the Andean region is especially vulnerable, as its agricultural production depends on stable climatic conditions to achieve adequate harvests. This study presents the development of an early warning system against frosts, based on an Internet of Things (IoT) architecture, which employs long-range Wireless Sensor Networks (WSNs) and supervised learning algorithms specifically decision trees to anticipate frost-prone conditions and issue timely alerts to farmers. This enables the adoption of preventive measures that minimize agricultural losses and strengthen the sector's resilience to extreme weather events. The research was conducted using the Action Research methodology, which involved an analysis of the phenomenon and the requirements of the stakeholders, followed by the design of a solution that included the selection of appropriate hardware and technologies, as well as the validation of technical requirements. The system was designed and implemented in a real agricultural environment, and the results demonstrated that the proposed solution is reliable, accurate, and adaptable, enabling timely frost detection and real-time alert generation. Furthermore, its effectiveness in crop protection was evident, contributing to the development of a more efficient, sustainable, and technologically advanced agriculture.

Keywords: Frost Control; Internet of Things (IoT); Wireless Sensor Networks (WSN); Machine Learning; Early Warning System; Agricultural Resilience; Climate Change.

RESUMEN

Las heladas constituyen un fenómeno climático adverso que impacta severamente la agricultura, provocando daños irreversibles en las plantas, este proceso genera deshidratación, deterioro del tejido vegetal y, en casos extremos, la pérdida total de los cultivos. La falta de estrategias eficaces de prevención y respuesta agrava sus consecuencias, ocasionando significativas pérdidas económicas, especialmente entre pequeños productores. En Ecuador, la región andina es particularmente vulnerable, ya que su producción agrícola depende de condiciones climáticas estables para lograr adecuadas cosechas. El presente trabajo presenta el desarrollo de un sistema de alerta temprana contra heladas, basado en una arquitectura de Internet de las Cosas (IoT), que emplea Redes de Sensores Inalámbricos (WSN) de largo alcance y algoritmos de aprendizaje supervisado como árboles de decisión que permiten detectar anticipadamente condiciones propensas a heladas y emitir alertas oportunas a los agricultores, facilitando la adopción de medidas preventivas que minimizan las pérdidas agrícolas y fortalecen la resiliencia del sector frente a eventos climáticos extremos. La investigación se condujo bajo la metodología Action Research, que incluyó el análisis del fenómeno, los requerimientos de los actores involucrados, para posteriormente realizar el diseño de la solución que incluyó la selección de hardware y tecnologías adecuadas, la validación de requerimientos técnicos. El sistema fue diseñado e implementado en un entorno agrícola real y los resultados alcanzados demostraron que la solución propuesta es confiable, precisa y adaptable, permitiendo la detección oportuna de heladas y la generación de alertas en tiempo real. Asimismo, se evidenció su eficacia en la protección de cultivos y su contribución al desarrollo de una agricultura más eficiente, sostenible y tecnológicamente avanzada.

Palabras clave: Control contra Heladas; Internet de las Cosas (Iot); Redes de Sensores Inalámbricos (WSN); Aprendizaje Automático; Sistema de Alerta Temprana; Resiliencia Agrícola; Cambio Climático.

INTRODUCTION

Frosts are a climatic phenomenon that significantly impact agriculture, causing irreversible damage to plants. This effect results from the freezing of water both inside and outside plant cells, which leads to dehydration, deterioration of plant tissue, and, in extreme cases, total crop loss.[1] The absence of preventive strategies and rapid response mechanisms exacerbates these effects, generating substantial economic losses in the agricultural sector.

In Ecuador, frosts have severely affected agricultural production, particularly in the Andean region, where small-scale farmers depend on stable climatic conditions for their livelihoods.[2] It is estimated that annual economic losses derived from extreme weather events, such as frosts and droughts, range between 927 million and 3,3 billion dollars,[3] highlighting the urgent need to implement early warning systems.

The development of technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) has transformed the agricultural sector, enabling precise and real-time monitoring of climatic variables. These innovations provide farmers with detailed data on weather conditions and crop health, facilitating decision-making based on reliable information. In this context, the implementation of a frost warning system aligned with the Development Plan for a New Ecuador (2024–2025) contributes to improving agricultural productivity sustainably, promoting the adoption of advanced technologies and preferential financial strategies.[4]

This work is also aligned with the United Nations Sustainable Development Goals (SDGs), impacting multiple areas. It contributes to SDG 2: Zero Hunger, by ensuring food availability through crop protection; to SDG 13: Climate Action, by mitigating the effects of climate change on agricultural production; and to SDG 9: Industry, Innovation, and Infrastructure, by fostering the adoption of advanced technologies in the agricultural sector.[5]

Therefore, the implementation of a long-range wireless technology-based alert system combined with supervised learning algorithms will allow early detection of frost events, providing timely alerts to farmers. This will facilitate the application of preventive measures to minimize agricultural losses and strengthen the sector's resilience to extreme weather events, fostering a more efficient and sustainable agricultural development.

METHOD

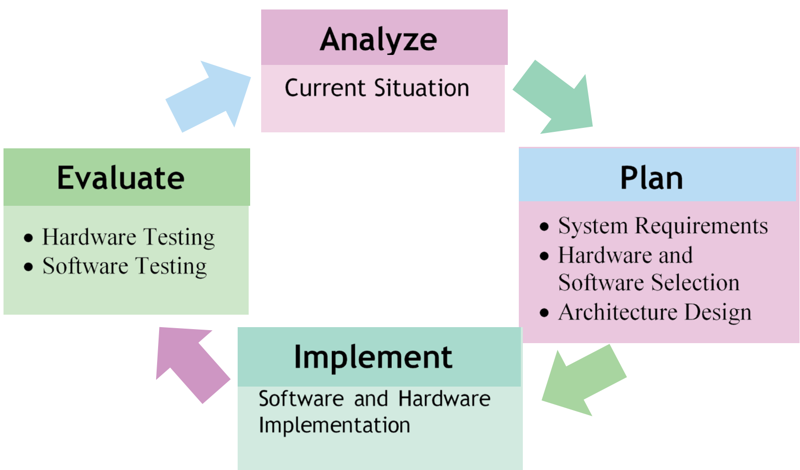

Figure 1. Action Research Work Methodology

Hardware and Software Selection

At this stage, the definition of both hardware and software components of the frost alert system is established. The needs and requirements of both farmers and developers are considered, based on the guidelines of ISO/IEC/IEEE 29148,[7] which defines how to specify requirements and nomenclature for systems and software. To achieve this, various available options are analysed and compared, selecting those that best fit the system according to their characteristics and performance. The chosen components are detailed below, based on the priority each one has within the system.[8,9]

Sensor Node Hardware

- ESP32-WROOM: microcontroller with wireless connectivity, responsible for processing and transmitting data[10]
- LoRa RFM95W Module: long-range communication with low energy consumption.[11]
- DHT11: temperature and humidity sensor.[12]
- Anemometer: sensor for measuring wind speed.
- GUVA-S12SD: sensor for measuring UV index.[13]
- Power Bank: power supply.

Gateway Node Hardware

- Arduino Uno: intermediary for receiving data from the sensor node.[14]
- Arduino Uno: intermediary for receiving data from the sensor. node[11]
- Raspberry Pi 3B: data processing and storage.[15]

Gateway Node Hardware

- Arduino IDE: hardware programming for sensor calibration and data transmission.

Gateway Node Software

- Arduino IDE: programming of the data-receiving hardware.
- InfluxDB: database for time-series data storage.
- Node-RED: integration platform for data processing.
- Mosquitto: MQTT broker for data transmission.
- Python (Scikit-learn): implementation of machine learning algorithms for frost risk detection.
- Telegram API: for sending alerts.

Frost Alert System Design with IoT Model

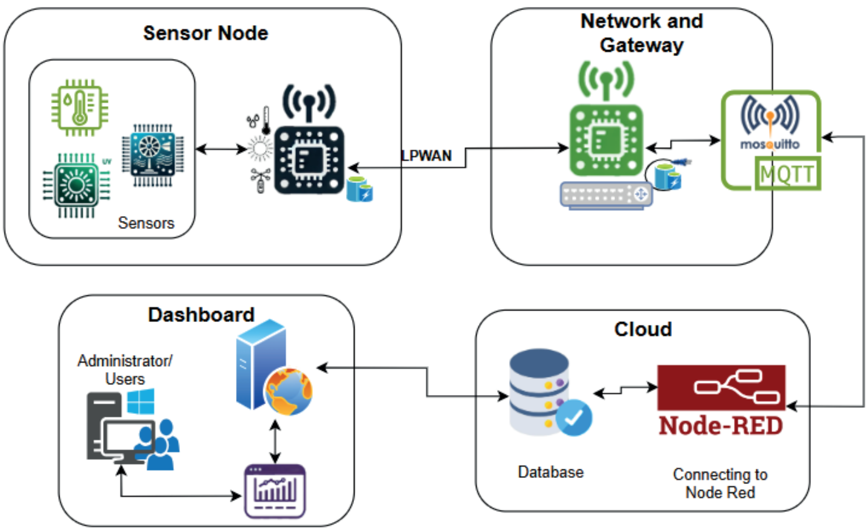

Figure 2. System design with IoT architecture

The diagram in figure 2 defines the structure of the frost alert system designed for sensitive crops. This system is based on an IoT architecture that integrates various essential components. First, the sensor node is responsible for collecting information on temperature, environmental humidity, UV radiation, and wind speed, using specific sensors for each parameter. Subsequently, the collected data are transmitted to the Gateway through LPWAN technology,[16] recognized for its low energy consumption and wide coverage range—ideal characteristics for implementation in remote agricultural environments.[17] The Gateway plays a key role as an intermediary in managing data received from the sensor nodes. Its main function is to process the information and send it to the cloud for secure and accessible storage. Once in the cloud, the data are recorded in a database that enables efficient access and management. At the application layer, the stored information is visualized through an intuitive graphical interface, facilitating real-time monitoring of meteorological conditions that may trigger frost events. Through the alert system, farmers receive early notifications about critical climate changes, enabling them to take timely preventive measures.

Sensor Node Connection Diagram

The connection scheme of the Sensor Node represents the integration between an ESP32, multiple sensors, and a LoRa module. The ESP32 serves as the central processing unit, responsible for collecting information from the sensors and transmitting it through the LoRa module. Among the connected sensors are an anemometer to measure wind speed, a DHT11 sensor to record temperature and humidity, and a GUVA-S12SD sensor to detect ultraviolet radiation. In addition, the connection wires are organized using a color-coding system that facilitates their identification and proper connection, see figure 3.

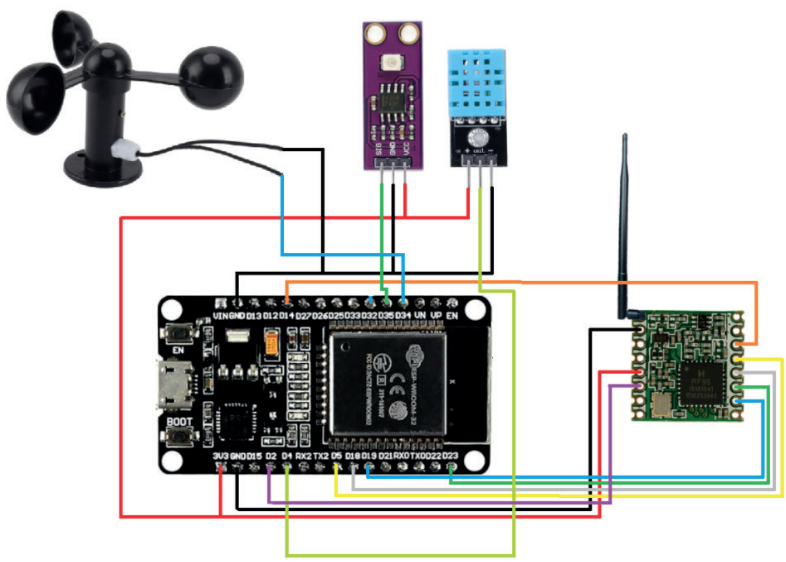

Figure 3. Sensor Node Connection Diagram

Gateway Node Connection Diagram

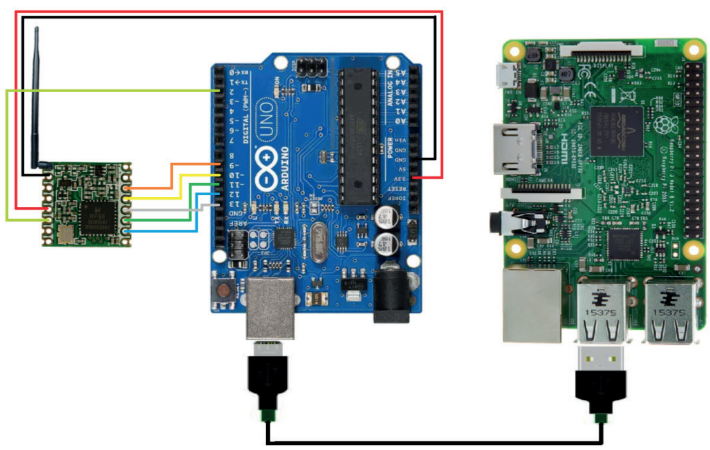

Figure 4. Gateway Node Connection Diagram

The Gateway connection diagram shown in figure 4 represents the interconnection between an Arduino Uno, a Raspberry Pi, and a LoRa module, which work together to receive and process data sent by the sensor node. In this configuration, the LoRa module is linked to the Arduino Uno, which acts as an intermediary, capturing the information from the LoRa module and transmitting it to the Raspberry Pi 3 Model, where the data is processed and displayed.

DEVELOPMENT

Once the configuration of each component has been completed and the corresponding connections established, the elements are assembled in each node. Subsequently, a verification process is carried out to ensure the optimal functioning of the system.

Sensor Node Integration

For the sensor node, which acts as the transmitter within the network, Figure 5 illustrates its main connections. In this configuration, the use of an ESP32-WROOM board stands out, integrated with three sensors: a DHT11 to measure temperature and humidity, an anemometer to measure wind speed, and the GUVA-S12SD sensor for ultraviolet radiation. It also incorporates the LoRa RFM95 module, responsible for communication between both stations. The entire system is powered by a 3V power bank, ensuring a stable and continuous energy supply.

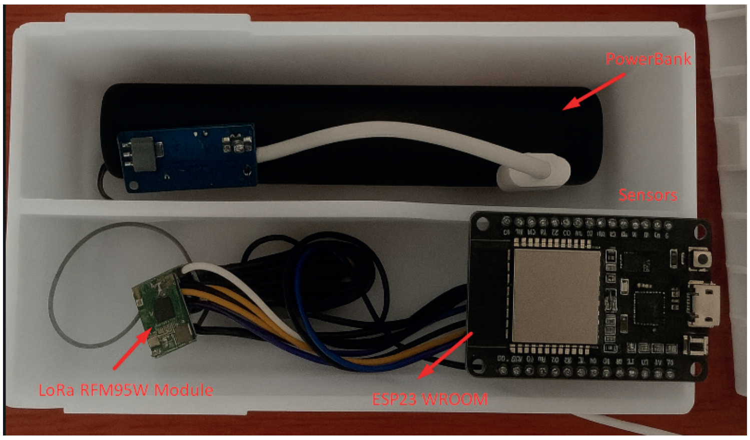

Figure 5. Integration of Sensor Node Components

Data Collection and Visualization in the Sensor Node

For the Gateway node, whose function is to receive data via LoRa communication, a serial link is first established between the Arduino UNO microcontroller and the Raspberry Pi 3. During this process, the RFM95 module captures the transmitted information, which is collected by the Arduino UNO and then sent to the Raspberry Pi 3 for processing through Node-RED and subsequent storage in InfluxDB. The final configuration of the LoRa Gateway node is shown in figure 6.

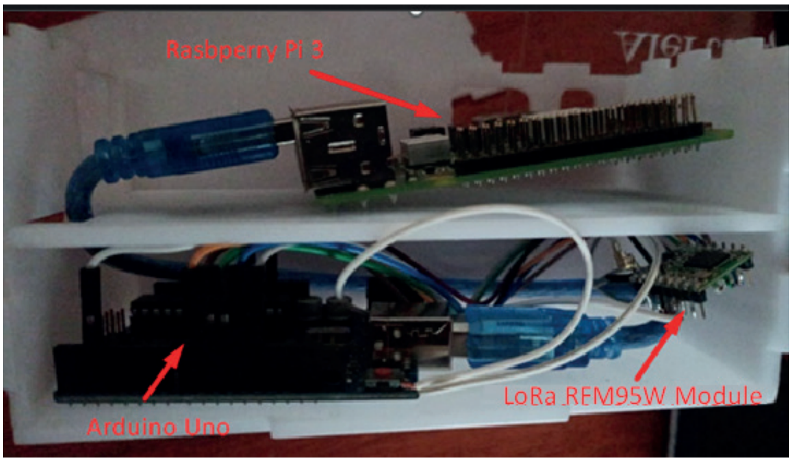

Figure 6. Integration of Gateway Node Component

Integration of Artificial Intelligence

Within AI, there are different types of approaches, among them supervised learning,[18] which encompasses several options adaptable to each project. After a brief analysis, the decision tree algorithm[19] was selected. This model fits perfectly with the project's objective, as it allows for different types of training and is expandable, considering the project's future development.[20] To this end, a database was built with input labels such as: station, time, temperature, humidity, wind speed, UV index, and frost occurrence. The station parameter is coded as 0 for summer and 1 for winter.

Conditions for Generating an Early Warning

There are critical values that may trigger an alert, as shown in table 1. These values represent the threshold levels for each of the variables considered. Since the values are independent, they could generate false negatives; however, to avoid this, the variables must be correlated with one another to activate an alert.

Table 1. Independent peak values

Variable	Critical condition
Temperature	<= 9,5 °C
Wind	<= 25 Km/h
Humidity	<=88 %
UV Index	<= 3,5
Season	= 1

Likewise, the dependency conditions for the occurrence of a frost warning phenomenon are configured. Table 2 shows this dependency of the analyzed variables.

Table 2. Dependent peak values

Variable	Critical condition	Condition of dependency
Temperature	<= 9,5 °C	With humidity > 88,0 %
Wind	<= 25 Km/h	With temperature > 9,5 °C
Humidity	<=88 %	If wind > 59,5 km/h
UV Index	<= 3,5	If wind > 59,5 km/h
Season	= 1	In conditions of high humidity and low wind

On the other hand, the dependencies of four conditions for the frost phenomenon are configured, taking temperature into account, as shown in table 3.

Table 3. Peak values dependent on temperature

Condition 1	Condition 2	Condition 3	Condition 4
Temperature ≤ 9,5°C	Wint ≤ 25 km/h	Does not exist	Does not exist
Temperature ≤ 9,5°C	Wint≤ 25 km/h	Humidity ≤ 88 %	Does not exist
Temperature ≤ 9,5°C	Wind ≤ 25 km/h	Humidity ≤ 88 %	Temp ≤ 7,5°C
Temperature ≤ 9,5°C	Wind ≤ 25 km/h	Humidity ≤ 88 %	station ≤ 1
Temperature ≤ 9,5°C	Wind ≤ 59,5 km/h	Does not exist	UV Index ≤ 3,5

There are also other conditions in which frost can be detected without prioritizing temperature; these are shown in table 4.

Table 4. Peak values dependent on temperature without prioritization

Condition 1	Condition 2	Condition 3
Wind ≤ 25 km/h	Humidity ≤ 88 %	Does not exist
Wind ≤ 25 km/h	Humidity ≤ 88 %	Station ≤ 0,5
Wind > 59,5 km/h	Does not exist	UV Index ≤ 3,5

Within Node-RED, the decision tree is integrated and trained with a robust database of 8240 records, taking into account different patterns and the potential occurrence of this phenomenon, resulting in 1030 linked data entries used for training. Evaluation metrics were also applied to the trained model,[21] including the percentage of correct predictions relative to the total number of evaluated samples, as well as cross-validation, which yielded an accuracy of 99,03 %.

RESULTS

This section details the integration of hardware and software into a single node, enabling communication between nodes through wireless technology. Additionally, it addresses the publication of the collected data with the aim of analyzing system performance through operational tests that allow its evaluation.

Test 1. Verification of Data Collection by the Sensor Node

To verify the correct functioning of the sensor node and the accuracy of the readings obtained from the integrated sensors, the serial monitor of the Arduino IDE development environment was used. This tool makes it possible to visualize in real time the values recorded by the DHT11, the anemometer, and the GUVA-S12SD sensor, facilitating the identification of possible measurement errors and ensuring that each sensor operates within the established parameters (figure 7). These data can be compared with those provided by the meteorological station,[22] showing identical or similar values with a minimal margin of error.

```
Sensor Node
LoRa module initialized. OK!
Spreading Factor (SF): 7
Bandwidth (BW): 125000
Coding Rate (CR): 4/5
Temperature A.: 20.60 °C, Humidity A.: 66.00 % Wind Speed: 0.00 km/h, UV Index: 0.00
Temperature A.: 20.60 °C, Humidity A.: 66.00 % Wind Speed: 0.00 km/h, UV Index: 0.00
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind Speed: 0.000.00 km/h, UV Index: 5.29
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind Speed: 0.000.00 km/h, UV Index: 5.03
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind speed: 0.000.00 km/h, UV index: 4.90
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind speed: 0.000.00 km/h, UV index: 5.11
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind speed: 0.000.00 km/h, UV index: 5.19
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind speed: 0.000.00 km/h, UV index: 4.68
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind speed: 0.000.00 km/h, UV index: 3.05
Temperature A.: 24.80 °C, Humidity A.: 43.00 % Wind speed: 0.000.00 km/h, UV index: 2.45
```

Figure 7. Data collection by the Sensor Node

Test 2. Verification of Data Reception by the Gateway Node

The Arduino is the first component in the Gateway flow, responsible for managing LoRa communication and receiving data from the sensor node. After capturing the information, it processes and sends it to the Raspberry Pi via serial communication. As shown in figure 8, the correct reception and processing of the data is verified, ensuring their integrity before storage and visualization. This phase is essential to guarantee smooth communication between the sensor node and the Gateway.

```
Data received: T:23.20 H:64.00 W:0.00 UV:0.00
Data processed:
Temperature: 23.20 °C
Humidity: 64.00 %
Wind speed: 0.00 km/h
UV index: 0.00
Data received: T:23.30 H:64.00 W:0.00 UV:0.00
Data processed:
Temperature: 23.30 °C
Humidity: 64.00 %
Wind speed: 0.00 km/h
UV index: 0.00
```

Figure 8. Verification of data reception by the Gateway Node (Arduino)

```
"
{"temperature":23.40, "humidity":63.00, "wind_speed":0.00, "uv":0.00}
"
2/2/2025 20:36:51 node: debug 2
msg.payload : string[66]

"
{"temperature":23.40, "humidity":63.00, "wind_speed":0.00, "uv":0.00}
"
```

Figure 9. Verification of Gateway Node Reception (Raspberry Pi)

The data are received through the serial port and visualized in real time using Node-RED. For this purpose, the Serial In node captures the information and sends it to the Debug node, allowing monitoring in the debug console. This facilitates the detection of communication errors, such as packet loss or data inconsistencies. As shown in figure 9, efficient reception without losses is verified, and the data are received in JSON String format.

Test 3. Reception and Verification in InfluxDB

On the InfluxDB platform, it is verified that the tags have been correctly generated and that the data are properly stored. For easier visualization, a table is used to examine the values recorded in real time. As shown in figure 10, this graphical representation provides a clear and organized way to analyze the information stored in the database.

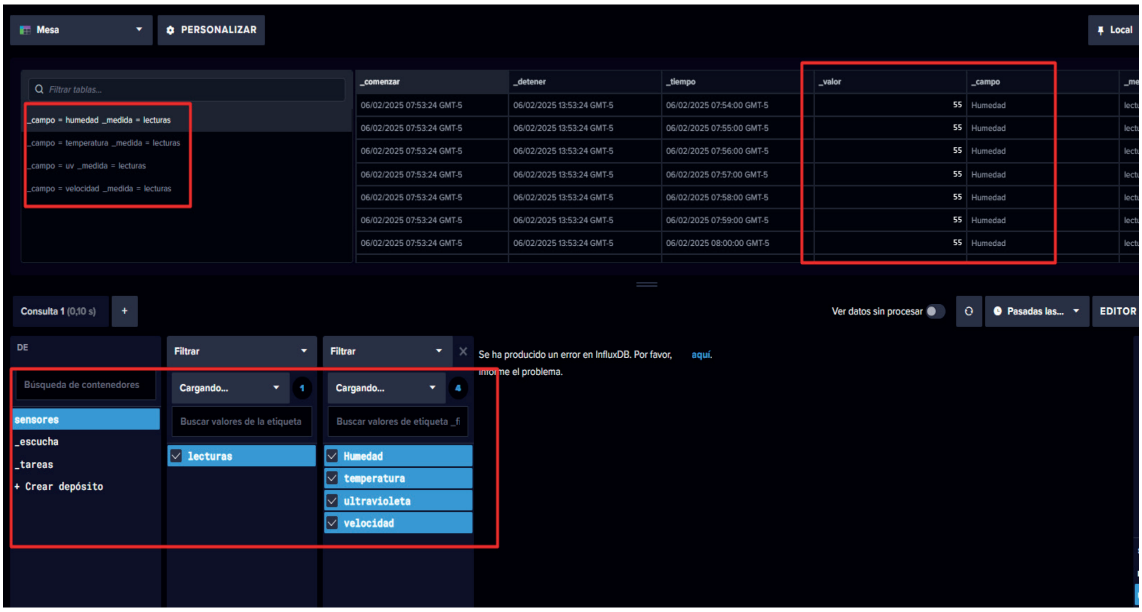

Figure 10. Verification of Data Reception in InfluxDB

Test 4. Reception and Verification in Grafana

Thanks to the direct connection between InfluxDB and Grafana, the stored data are visualized in real time through customized dashboards. The database is configured as a data source in Grafana, automatically updating every 5 seconds. This enables an accurate and dynamic representation of the information collected by the sensors, facilitating analysis and pattern detection. In addition, Grafana offers customization options to optimize data visualization.

Figure 11. Verification of Data Reception in Grafana

Verification of AI Functionality

The integration of the decision tree with Node-RED is verified using real-time sensor data. The system evaluates temperature, humidity, wind speed, and UV index to predict the occurrence of frost. With normal data, the model determines that no frost is expected under current conditions, while with favorable conditions it predicts its occurrence when the data indicate risk. These results confirm the accuracy of the decision tree and its reliability in automating climate analysis.

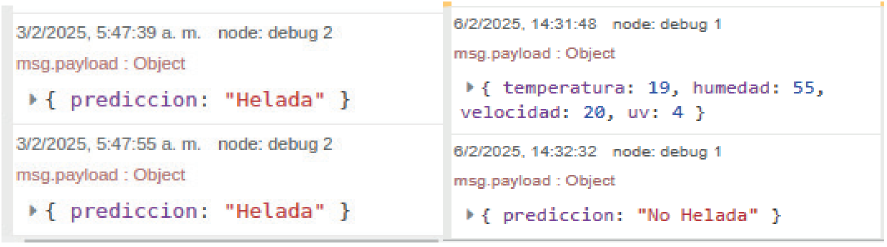

Figure 12. Verification of Prediction with AI

Test 6. Verification of Alert Delivery in Telegram

Alerts in Telegram are activated only when the decision tree predicts the occurrence of frost, ensuring that notifications are sent exclusively in relevant situations. For this purpose, an automated bot transmits a predefined message to the user. As shown in figure 13, the alert includes a warning icon to quickly capture attention, along with a brief description of the event, recommending precautionary measures against adverse weather conditions

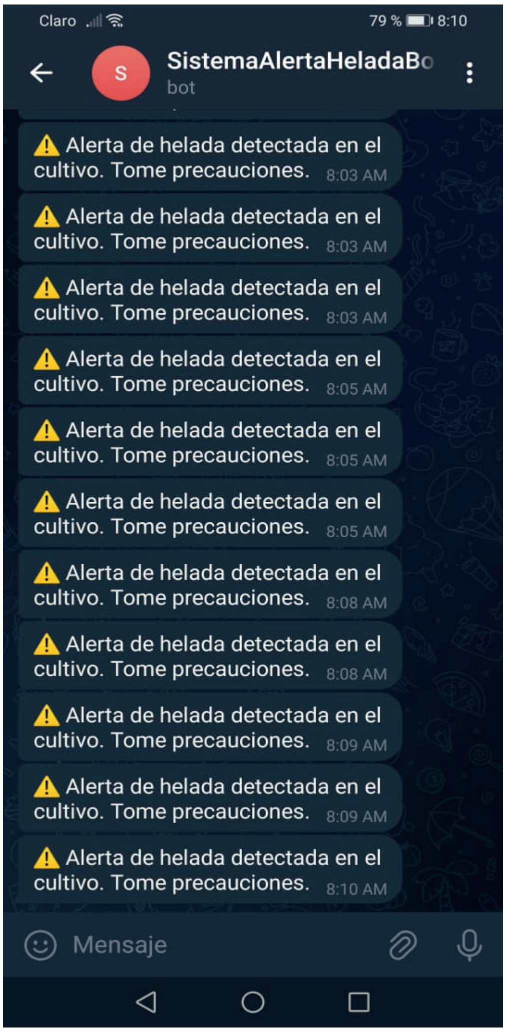

Figure 13. Verification of Alerts Issued in Telegram

Data Logging Analysis

The system operates throughout the entire crop cycle, from germination to harvest, continuously monitoring environmental variables to detect possible frost events. In table 5, no frost indicators were recorded during the day, since temperature, humidity, wind speed, and UV index remained at stable levels, ensuring favorable weather conditions with no risk of freezing.

Table 6 presents nighttime data indicating conditions conducive to frost, highlighting temperature as a key factor. During the early morning hours, a drop in temperature can trigger system alerts, allowing for preventive action. In winter, the increased risk leads to more frequent alerts, so the system issues more alerts during this period.

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Table 5. Data Log During the Day				
Date and time	**Temperature (°C)**	**Humidity (%)**	**Wind speed (Km/h)**	**UV index**
2024/07/17 09:15:15	13	65	35	1
2024/07/17 10:15:15	14	65	0	2
2024/07/17 11:15:15	17	53	0	5
2024/07/17 12:15:15	18	51	49	9
2024/07/17 13:15:15	17	52	30	7
2024/07/17 14:15:15	15	66	0	3
2024/07/17 15:15:15	13	65	51	4
2024/07/17 16:15:15	14	63	0	4
2024/07/17 17:15:15	12	50	0	2

Table 6. Data recording during the night and early morning				
Fecha y Hora	**Temp. (°C)**	**Hum. (%)**	**V. Vien. (Km/h)**	**UV.**
2024/07/16 18:15:15	10	85	29	0
2024/07/16 19:15:15	10	81	0	0
2024/07/16 20:15:15	12	82	8	0
2024/07/16 21:15:15	11	85	30	0
2024/07/16 22:15:15	11	82	30	0
2024/07/16 23:15:15	9	60	0	0
2024/07/17 24:15:15	9	54	20	0
2024/07/17 01:15:15	9	58	0	0
2024/07/17 02:15:15	9	62	0	0
2024/07/17 03:15:15	7	40	19	0
2024/07/17 04:15:15	7	34	0	0
2024/07/17 05:15:15	9	50	0	0
2024/07/17 05:30:00	9	60	28	0

DISCUSSION

Assessment of Crop Loss Reduction: Frost events can cause severe damage to crops, reducing yield and affecting farmers' income. In extreme cases, they may result in total losses, while partial damages also lead to significant economic impacts. The Frost Alert System helps mitigate these risks by providing real-time information about conditions favorable for frost formation. This enables the implementation of preventive measures such as irrigation, thermal coverings, or heating, thereby minimizing damage. Its early detection and alerting capability make it an essential tool for protecting agricultural production. However, conducting an evaluation of crop loss reduction using historical data is not feasible, since the area where the system was implemented does not have a recorded history of this phenomenon, which makes the analysis difficult.

CONCLUSIONS

The Frost Alert System has proven to be an effective solution for mitigating the effects of this phenomenon through the integration of IoT and Artificial Intelligence. Its implementation enables real-time monitoring of climatic variables and the issuance of early alerts, helping to prevent crop losses and optimize farmers' responses. The prior research facilitated the selection of suitable technologies and efficient Artificial Intelligence techniques, ensuring the system's accuracy. Moreover, the definition of software and hardware requirements made it possible to develop a solution tailored to the agricultural environment, guaranteeing reliability and functionality. The IoT-based architecture and LoRa communication allow the system to be expanded to different agricultural regions with minimal modifications, adapting to diverse climatic conditions and crop types. The integration of Artificial Intelligence has optimized decision-making through automated analysis of climatic data, reducing the need for manual intervention and improving responsiveness to critical events. The tests conducted confirm that the system operates with high precision and stability, providing real-time alerts with a low rate of false positives, thereby reinforcing its reliability in crop management. The system has been designed with low-power technology, making it sustainable and viable for implementation in rural areas with limited access to electricity

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