ANALYSIS OF CLIMATIC AND EDAPHIC VARIABLES OF STARCHY CORN CROPS WITH THE APPLICATION OF INTERNET OF THINGS (IOT) IN PAMPAS-HUANCAVELICA, PERU

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SUMMARY

This article presents the implementation and results of an Internet of Things (IoT) system for monitoring climatic and edaphic variables in starchy corn crops under greenhouse conditions in Huancavelica, Peru. The system comprises two end nodes, a LoRa gateway, and a graphical user interface. Each end node is equipped with sensors to measure and transmit data on relative humidity and temperature (climatic variables), as well as soil moisture, temperature, electrical conductivity (EC), and pH (edaphic variables). The LoRa gateway ensures data transmission from the end nodes to the Internet, enabling real-time visualization of recorded data through the graphical user interface. This setup facilitated the analysis of the dynamics of the variables, revealing distinct patterns in greenhouse conditions. Relative and soil temperatures peaked at midday and decreased at night, while relative and soil humidity were higher in the early morning. Greenhouse 2 maintained stable pH and EC levels, whereas Greenhouse 1 showed an EC peak of 13 and a pH of 6.5, likely due to consistent irrigation practices. The IoT system demonstrated its reliability and efficiency, even in remote areas with limited Internet connectivity, highlighting its robustness under challenging conditions. By automating data collection and enabling remote monitoring, this system supports timely and precise decision-making, offering valuable insights into crop conditions and improving agricultural management. The implementation of such systems in greenhouse environments optimizes resource use, enhances productivity, and provides a scalable solution for precision agriculture in regions with limited technological infrastructure.

Introduction

The environment plays a crucial role in determining crop quality and production, posing challenges for maintaining optimal conditions under typical circumstances. Advanced technologies are essential to address these challenges, enabling predictive capabilities and supporting informed decision-making (García-Mendoza *et al*., 2021). With the growing economic importance of agriculture and increasing market demands, numerous researchers have focused on modernizing the industry through solutions aimed at controlling variables that impact crop productivity and quality while alleviating the workload of farmers. These efforts have also contributed to the development of precision agriculture applications, which optimize resource use and increase efficiency (Ferrández-Pastor *et al*., 2016).

KEYWORDS / Agricultural Automation / Edaphoclimatic Variables / Greenhouse Production / Iot / Lora / Precision Agriculture / Starchy Maize /

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The integration of the Internet of Things (IoT) into agriculture has been transformative, enabling rapid data transmission and real-time visualization of critical parameters. These advancements have significantly enhanced agricultural activities by improving monitoring and reducing production costs through efficient control of variables affecting crop growth. Recent developments in low-power wide-area networks (LPWANs), including SigFox, LoRa, and NB-IoT, have further facilitated the adoption of IoT by overcoming limitations in data transmission range and supporting scalability (Miles *et al*., 2020).

Several IoT-based agricultural solutions have been implemented worldwide, addressing diverse crop needs. In Peru, IoT systems have been deployed for optimizing banana, mango, and bean production (Oquelis Guerrero and Landa Vega, 2020; Rosas Pari, 2019). In Ecuador, wireless sensor networks (WSNs) have been used for monitoring environmental parameters in cocoa crops, while in Indonesia, IoT systems were designed to track pH and soil moisture for star fruit cultivation (Ordoñez Obando and Ruiz Quimis, 2021; Rachmani and Zulkifli, 2018). In Thailand, LoRaWAN-enabled IoT systems monitored climatic and edaphic conditions to optimize crop management (Boonyopakorn and Thongna, 2020).

By automating data collection and facilitating remote monitoring, these IoT systems support informed decision-making for key agricultural practices like irrigation and fertilization (Zavaleta, 2020). They also demonstrate reliable performance in remote locations with limited internet connectivity, ensuring scalability and robustness in challenging environments. The system's potential to optimize resource use and enhance productivity makes it a valuable tool for sustainable agriculture, particularly in regions with constrained technological infrastructure (Kumar *et al*., 2024). Maize cultivation is particularly sensitive to both soil moisture deficits and excessive levels, compared to other crops. The growth stage, in particular, requires the highest amount of water, as it is the phase during which the plant produces the largest quantity of dry matter (Cicioğlu and Çalhan, 2021). In this context, the main objective of this study was to design and implement an Internet of Things (IoT) system to monitor climatic and edaphic variables in maize cultivation under greenhouse conditions in Huancavelica, Peru, in 2022. The specific objectives were: (1) to design and implement a low-power electronic device as part of the IoT system for monitoring maize crops in Huancavelica in 2022; (2) to implement a wireless gateway for data transmission in the IoT system; and (3) to develop a web-based user interface for visualizing and analyzing the monitored data. This system enables the collected data to be used for precise decision-making in various essential practices, such as determining the appropriate fertilization methods and irrigation types, which are critical for the successful cultivation of maize. By facilitating these precise interventions, the system contributes to optimizing crop production processes, ensuring efficient resource use and better yield outcomes.

Methodology

Two key phases were defined for data collection. During the first phase, connectivity tests were conducted for IEEE802.11 networks, mobile networks, and LoRa. In the second phase, sensor functionality tests were performed. After verifying the proper operation of the sensors, the collection of climatic and edaphic variables for maize crops was carried out.

Before finalizing the selection of components, an initial prototype was designed to identify the most optimal and suitable components for addressing the identified challenges. The implementation of an intelligent system, which facilitated the monitoring and analysis of climatic and edaphic variables, made it possible to understand their behavior in detail, consisting of :

- Two electronic devices (end nodes) were installed in two greenhouses. These end nodes measured relative humidity and temperature, soil moisture, soil temperature, electrical conductivity, and soil pH.
- A gateway was installed at the Universidad Nacional Autónoma de Tayacaja (UNAT) facilities; the distance between the UNAT facility and the greenhouses is around 1 km. Finally, a LoRa server and a Web server were installed on an AWS EC2 Linux instance.

A LoRa server and a Web server were installed on an AWS EC2 Service Linux machine (Figure 1).

Specialized sensors were used to measure greenhouse variables with precision, as detailed in Table I. Following this, modules for the end nodes and the gateway were installed to transmit the collected data, along with software to display it, as shown in Table II.

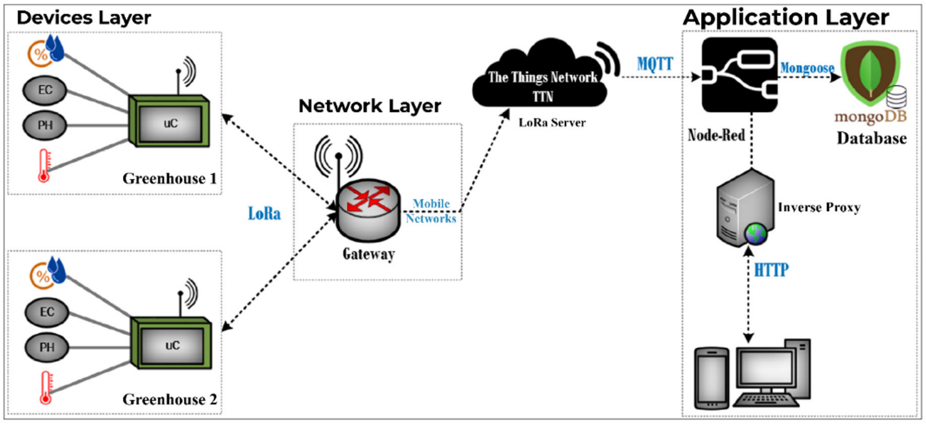


Figure 1. Architecture of the IoT System.

TABLE I
SENSORS EMPLOYED

Sensors	Measurement
DHT22	Humidity and temperature
Catnip	Soil humidity and temperature
RS485	pH and electric conductivity

TABLE II
END NODES COMPONENTS

Components	Purpose
RAK3272S	Connectivity to mobile networks
ESP32 DEV KIT	Development cards
Baby Buck	Voltage regulator S
Raspberry pi and HAT RAK2245	LoRa gateway
Wisgate Edge Lite 2 RAK7268C	LoRa gateway

Selection of Sensors

Within the greenhouses, ambient temperature and relative humidity were measured, while soil-level measurements included temperature, moisture, pH, and electrical conductivity (EC). Sensor selection was based on technical criteria such as precision, resolution, operating range, and cost. Additionally, compatibility with microcontrollers, communication protocols, power supply voltage, and the availability of libraries in the MicroPython programming language were considered. The sensors employed to measure the parameters are described in Table I, along with the components for the end nodes to connect all the network, as shown in Table II.

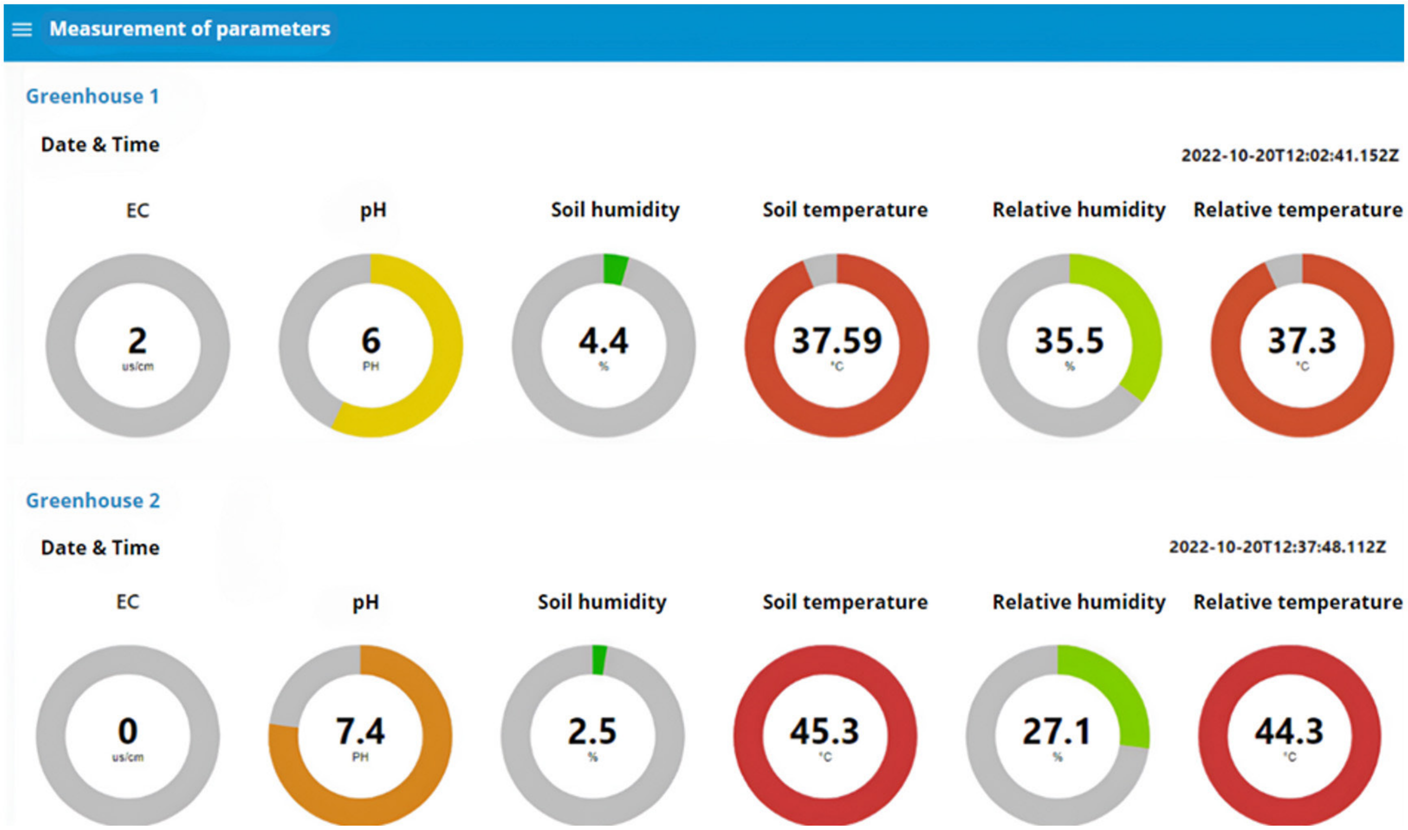
The monitoring period was conducted during the maize growth stages between V4 and V6, the most sensitive stages to abrupt changes in temperature and humidity. Measurements were recorded daily at 00:00:00, 06:00:00, 12:00:00, and 18:00:00. However, the first reading of each cycle was disregarded to ensure sensor reliability, with the second reading being used for analysis. Measurements included soil moisture, temperature, pH, EC, and ambient temperature and humidity. Confidence intervals were calculated for all monitored variables using a formula based on Student's t-distribution, as the population variance was unknown. According to Walpole *et al*. (2012), the formula used was:

$$\text{IC}\mu = \bar{X} \left(t_{\frac{\alpha}{2}} S / \sqrt{n} \right) \quad (1)$$

where ICμ is the confidence interval for the mean, $\overline{X}$ is the sample mean, tα/2 is the two-tailed Student's t-value, SSS is the sample standard deviation, and nnn is the sample size.

Results

The data in Figure 2 displays the measurements for both Greenhouse 1 and Greenhouse 2, taken from September 15 to October 15. The data were collected at various intervals to observe the evolving values over time, revealing differences in soil humidity, temperature, relative humidity, and



Greenhouse 1

Date & Time 2022-10-20T12:02:41.152Z

EC 2 us/cm
pH 6 PH
Soil humidity 4.4 %
Soil temperature 37.59 °C
Relative humidity 35.5 %
Relative temperature 37.3 °C

Greenhouse 2

Date & Time 2022-10-20T12:37:48.112Z

EC 0 us/cm
pH 7.4 PH
Soil humidity 2.5 %
Soil temperature 45.3 °C
Relative humidity 27.1 %
Relative temperature 44.3 °C

Figure 2. Dashboard to visualize climatic and edaphic variables.

ambient temperature between the two greenhouses.

Greenhouse 1

Regarding the duration of data collection for each variable (pH, EC, soil humidity and temperature, humidity, and ambient temperature), the following was considered: for the crop without irrigation, data collection began on 10/04/2022 and ended on 10/12/2022 in the morning; while for the irrigated crop, data collection began on 10/12/2022 at noon and ended on 11/10/2022.

Table III and Figure 3 shows the average soil pH value before and after the crops were irrigated, along with the time of data collection. In addition, the actions taken by the supervisor when the pH value was greater than 7 are displayed.

The average value of electrical conductivity (EC) of the crops before and after irrigation, and the time of data collection, is also shown in Table III and Figure 4. Furthermore, the actions taken by the supervisor when the EC was 1 or lower are listed.

Table IV shows the average value of soil moisture before and after the crops were watered and at the time the sensor collected the information (Figure 5). Additionally, the actions taken by the supervisor when the moisture value was less than 15% are shown.

On the other hand, Table IV also shows the average soil temperature before and after irrigation was applied, along with the actions taken if the temperature was lower than 10°C or higher than 35°C.

The last variable evaluated was the average ambient temperature and humidity before and after irrigation was applied (Table V and Figure 6). It also shows the intervals when the data were collected and the actions taken if the temperature was below 6°C.

Greenhouse 2

Table VI and Figure 7 shows the average soil pH value and the

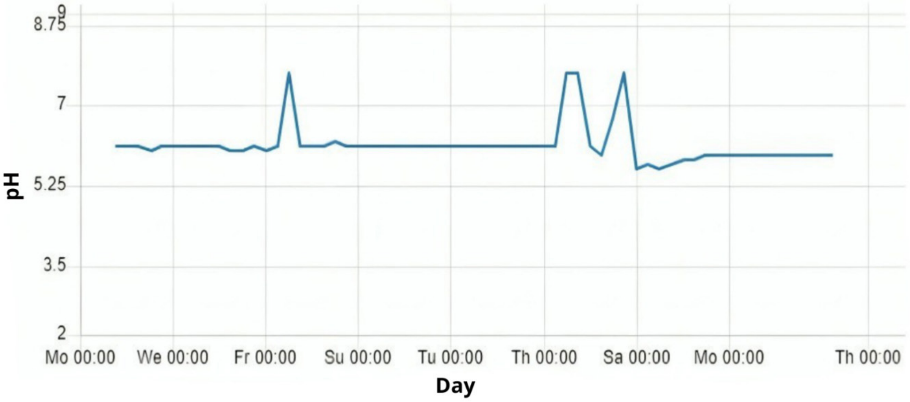


Figure 3. Soil pH measurements-irrigated crops in Greenhouse-1.

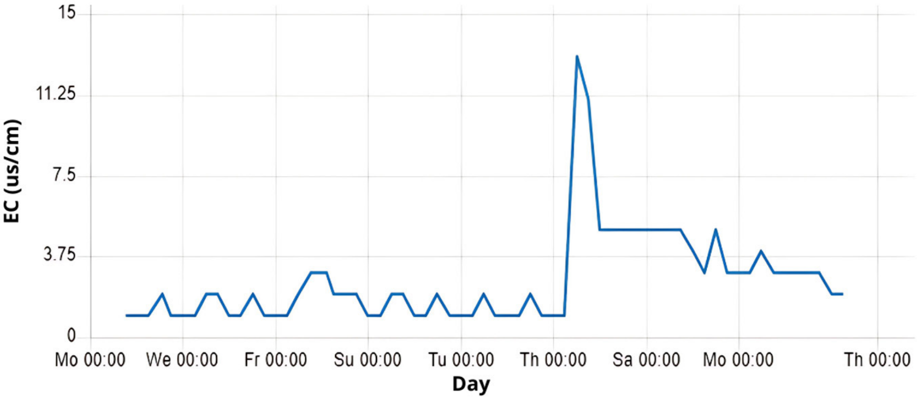


Figure 4. Soil electric conductivity (EC) measurements-irrigated crops in Greenhouse 1.

TABLE III

AVERAGE SOIL PH AND ELECTRIC CONDUCTIVITY (EC) VALUE - GREENHOUSE 1

Crop condition	Average soil pH value /Time				
	00:00	06:00	12:00	18:00	CI
Crop with irrigation	7.28	7.19	7.33	7.36	7.17; 7.41
Crop without irrigation	6.03	6	6.42	6.21	5.86; 6.47
Action taken if pH > 7	fertilizer application				
	Average soil EC value /Time				
Crop with irrigation	2.62	2.54	3.68	3.2	2.16; 3.86
Crop without irrigation	0.00	0.00	0.00	0.00	0.00; 0.00
Action taken if EC ≤ 1	sprinkler irrigation				

CI: Confidence intervals; EC: Electric conductivity.

TABLE IV
AVERAGE SOIL MOISTURE (%) AND TEMPERATURE (°C) – GREENHOUSE 1

Crop condition	Average soil moisture (%) /Time				
	00:00	06:00	12:00	18:00	CI
Crop with irrigation	18.26	18.33	18.88	18.86	18.05; 19.11
Crop without irrigation	10.86	11.44	8.14	10.05	7.83; 12.41
Action taken if H < 15	sprinkler irrigation				
	Average soil temperature (°C) /Time				
Crop with irrigation	9.03	9.03	9.03	9.03	9.03; 9.03
Crop without irrigation	11.24	11.24	11.24	11.24	11.24; 11.24
Action taken if T < 10 or T > 35	sprinkler irrigation				

CI: Confidence intervals.

TABLE V
AVERAGE ENVIRONMENT TEMPERATURE (°C) – GREENHOUSE 1

Crop condition	Temperature (°C) /Time				
	00:00	06:00	12:00	18:00	CI
Crop with irrigation	29.58	32.78	1.64	15.37	-2.91; 42.60
Crop without irrigation	34.59	36.91	5.38	22.56	1.90; 47.82
Action taken if H < 35	sprinkler irrigation				

CI: Confidence intervals.

intervals at which the sensor took measurements. Even though the greenhouse was not irrigated, the data were collected to evaluate the climatic and edaphic variables. The average soil humidity and soil temperature are also shown in Table VI and Figure 8.

The pH and humidity variables showed greater variation in Greenhouse 1 than in Greenhouse 2 (Tables III, IV, and VI), possibly because Greenhouse 1 was under cultivated conditions and irrigation was applied, while Greenhouse 2 was not cultivated and therefore did not receive irrigation. When the soil is cultivated, it has a greater buffer capacity to temperature variations. Although ambient temperature fluctuations between the two greenhouses (see Tables V and VI; Figure 9) were similar, it suggests that the crop has less influence on the conditions in Greenhouse 2.

Discussion

Both in Peru and worldwide, various solutions based on the Internet of Things (IoT) have been designed and implemented to monitor and control key environmental parameters in agricultural production. The results of these studies highlight the utility of such systems for informed decision-making in agriculture, relying on precise data rather than intuitive methods, thus improving agricultural efficiency. To date, most IoT applications have focused on fruit or vegetable crops (Rachmani and Zulkifli, 2018; Oquelis and Landa, 2020), with limited application to other crops such as maize, and even less to starchy corn.

This study contributes to enhancing the productive efficiency of starchy corn cultivation in the Peruvian highlands by automating the monitoring

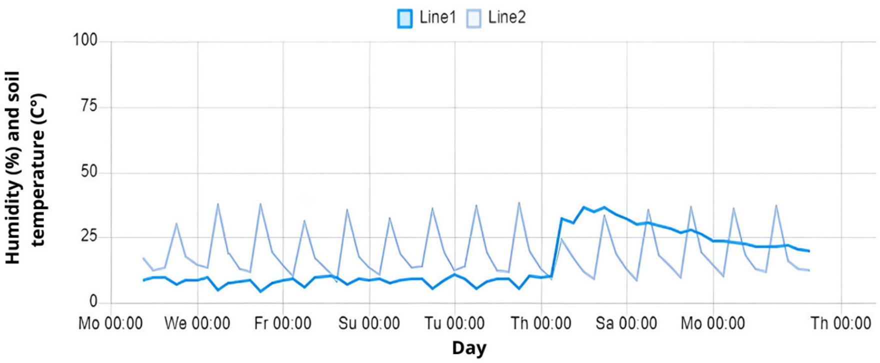


Figure 5. Soil moisture and temperature measurements irrigated crops. Line1: soil moisture; Line2: soil temperature. Greenhouse-1.

of critical climatic and edaphic variables. These parameters can be monitored remotely, enabling timely and appropriate decision-making. A significant aspect of this study is the system's reliable performance in a remote experimental location. Despite the gateway being 1km from the monitoring site, the Internet signal was efficiently captured, with no interruptions in the transmission of greenhouse data. This underscores the robustness of the system and its potential for application in similarly challenging agricultural environments, allowing the automation and remote supervision of critical crop parameters.

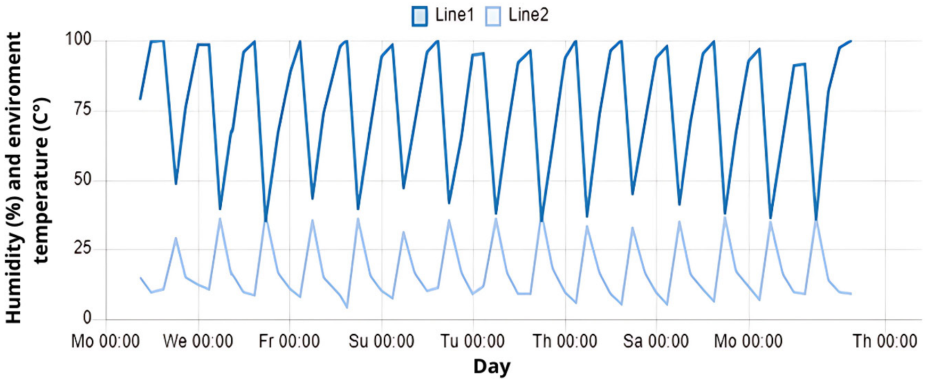


Figure 6. Environment temperature and humidity measurements - irrigated crops. Line1: environment humidity; Line2: environment temperature. Greenhouse-1.

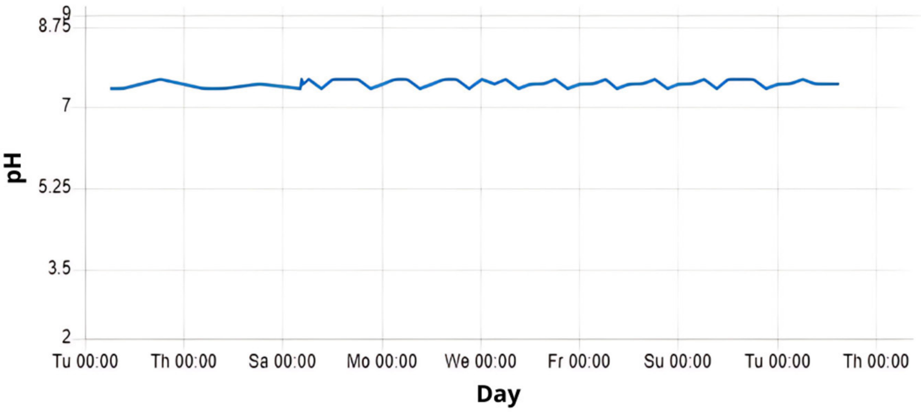


Figure 7. Soil pH measurements in Greenhouse-2.

As evaluated by Raj *et al*. (2021), the integration of information and communication technologies in agriculture, emphasizing Agriculture 4.0 – a combination of interconnected agriculture, precision farming, and Big Data Analytics – has demonstrated positive effects on production and various applications of smart agriculture. Similarly, Maraveas and Bartzanas (2021) highlight that while IoT technology implementation involves high costs, it offers substantial long-term benefits, becoming indispensable in greenhouses for precise control of crops during phenological stages. Considering the impact of climate change on crop development and commercialization, IoT systems in greenhouses represent a prudent decision for improved control and faster management responses.

Such technologies can integrate automation and precision agriculture to facilitate decision-making and implement preventive and immediate measures tailored to crop needs. Studies by Kim *et al*. (2020) and Boursianis *et al*. (2022) demonstrate the role of IoT in agriculture, particularly in utilizing unmanned technology to optimize response times. They also emphasize that advancements in wide-range signal transmission enhance the ability to send larger amounts of data to different locations globally, further optimizing agricultural practices.

Conclusions

The relative and soil temperature values for both greenhouses showed high peaks in their measurements at noon, while they decreased at night.

The relative and soil humidity values for both greenhouses

TABLE VI
AAVERAGE SOIL AND ENVIRONMENT VARIABLES VALUE IN CROP WITHOUT IRRIGATION - GREENHOUSE 2

Time		Soil variables		Environment variables	
	pH	Humidity	Temperature	Humidity	Temperature
00:00	7.52	6.54	10.96	82.91	8.5
06:00	7.52	6.54	10.84	84.89	7.86
12:00	7.52	6.54	42.06	30.1	40.28
18:00	7.52	6.54	16.54	58.53	14.89
CI	7.52; 7.52	6.54; 6.54	-3.57; 43.77	23.31; 104.91	-6.40; 42.17

CI: Confidence intervals.

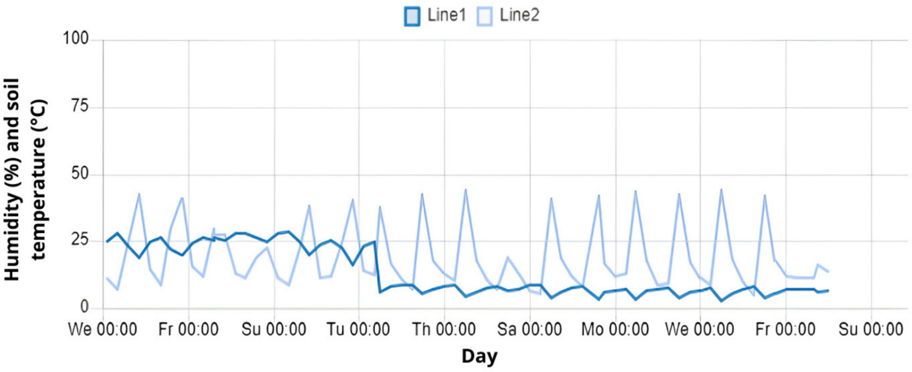


Figure 8. Environment temperature and humidity measurements. Line1: soil humidity; Line2: soil temperature. Greenhouse-2.

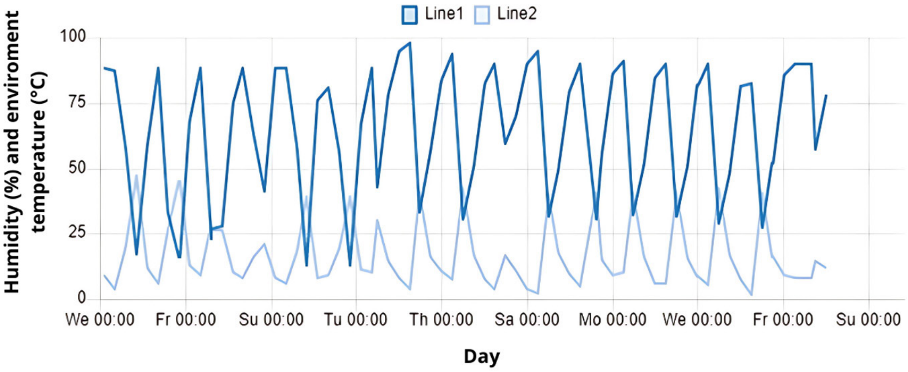


Figure 9. Environment temperature and humidity measurements. Line1: environment humidity; Line2: environment temperature. Greenhouse-2.

showed high peaks in the morning, while they decreased during the afternoon.

The pH and EC values remained constant in Greenhouse 2, while in Greenhouse 1, the maximum EC peak was 13 and the pH was 6.5. This behavior was due to the crop in Greenhouse 1 being continuously irrigated.

The system enabled remote monitoring of climatic and edaphic parameters, facilitating timely and appropriate decision-making. It demonstrated the ability to operate effectively in remote locations with limited internet connectivity, ensuring reliable performance even under challenging conditions.

If rapid information transfer is necessary and the internet bandwidth is very low, it is optimal to use a platform that allows the compression of data files, enabling quick visualization and efficient usage of the data obtained. However, this can vary depending on the amount of data that has to be transferred.

CONFLICTS OF INTEREST

All authors declare that there is no conflict of interest.

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ANÁLISIS DE LAS VARIABLES CLIMÁTICAS Y EDÁFICAS DE LOS CULTIVOS DE MAÍZ ALMIDONERO CON LA APLICACIÓN DE INTERNET DE LAS COSAS (IOT) EN PAMPAS-HUANCAVELICA, PERÚ

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RESUMEN

Este artículo presenta la implementación y los resultados de un sistema de Internet de las Cosas (IoT) para monitorear variables climáticas y edáficas en cultivos de maíz almidonero bajo condiciones de invernadero en Huancavelica, Perú. El sistema comprende dos nodos finales, una puerta de enlace LoRa y una interfaz gráfica de usuario. Cada nodo final está equipado con sensores para medir y transmitir datos sobre la humedad relativa y la temperatura (variables climáticas), así como la humedad del suelo, la temperatura, la conductividad eléctrica (EC) y el pH (variables edáficas). La puerta de enlace LoRa asegura la transmisión de datos desde los nodos finales a Internet, lo que permite la visualización en tiempo real de los datos registrados a través de la interfaz gráfica de usuario. Esta configuración facilitó el análisis de la dinámica de las variables, revelando patrones distintivos en las condiciones del invernadero. Las temperaturas relativas y del suelo alcanzaron su punto máximo al mediodía y disminuyeron por la noche, mientras que la humedad relativa y del suelo fueron más altas a primera hora de la mañana. El invernadero 2 mantuvo niveles estables de pH y EC, mientras que el invernadero 1 mostró un pico de EC de 13 y un pH de 6.5, probablemente debido a prácticas de riego consistentes. El sistema IoT demostró su fiabilidad y eficiencia, incluso en áreas remotas con conectividad a Internet limitada, destacando su robustez bajo condiciones desafiantes. Al automatizar la recolección de datos y permitir la supervisión remota, este sistema respalda la toma de decisiones oportuna y precisa, ofreciendo valiosos conocimientos sobre las condiciones de los cultivos y mejorando la gestión agrícola. La implementación de estos sistemas en entornos de invernadero optimiza el uso de los recursos, aumenta la productividad y ofrece una solución escalable para la agricultura de precisión en regiones con infraestructura tecnológica limitada.

ANÁLISE DAS VARIÁVEIS CLIMÁTICAS E EDÁFICAS DAS CULTURAS DE MILHO AMILÁCEO COM A APLICAÇÃO DA INTERNET DAS COISAS (IOT) EM PAMPAS-HUANCAVELICA, PERU

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RESUMO

Este artigo apresenta a implementação e os resultados de um sistema de Internet das Coisas (IoT) para monitorar variáveis climáticas e edáficas em culturas de milho amiláceo sob condições de estufa em Huancavelica, Peru. O sistema é composto por dois nós finais, um gateway LoRa e uma interface gráfica de usuário. Cada nó final é equipado com sensores para medir e transmitir dados sobre umidade relativa e temperatura (variáveis climáticas), bem como umidade do solo, temperatura, condutividade elétrica (EC) e pH (variáveis edáficas). O gateway LoRa garante a transmissão de dados dos nós finais para a Internet, permitindo a visualização em tempo real dos dados registrados por meio da interface gráfica de usuário. Essa configuração facilitou a análise da dinâmica das variáveis, revelando padrões distintos nas condições da estufa. As temperaturas relativa e do solo atingiram seu pico ao meio-dia e diminuíram à noite, enquanto a umidade relativa e do solo foram mais altas pela manhã cedo. A estufa 2 manteve níveis estáveis de pH e EC, enquanto a estufa 1 apresentou um pico de EC de 13 e um pH de 6,5, provavelmente devido a práticas de irrigação consistentes. O sistema IoT demonstrou sua confiabilidade e eficiência, mesmo em áreas remotas com conectividade à Internet limitada, destacando sua robustez em condições desafiadoras. Ao automatizar a coleta de dados e possibilitar o monitoramento remoto, esse sistema apoia a tomada de decisões pontuais e precisas, oferecendo valiosas informações sobre as condições das culturas e aprimorando a gestão agrícola. A implementação desses sistemas em ambientes de estufa otimiza o uso de recursos, aumenta a produtividade e oferece uma solução escalável para a agricultura de precisão em regiões com infraestrutura tecnológica limitada.