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Internet of things meteorological station for climate monitoring and crop optimization in Carabayllo-Perú

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ABSTRACT

In the agricultural sector, monitoring environmental variables such as temperature, humidity, and atmospheric pressure is crucial for efficient and sustainable agriculture. However, conventional monitoring systems are expensive and need more autonomy, making their implementation difficult in small- and medium-scale agricultural operations. This study presents the design, implementation, and evaluation Internet of things (IoT)-based autonomous for watch remote critical climate variables in the Carabayllo region, Peru. The system uses a data acquisition, processing, and transmission architecture based on the ESP32 microcontroller, DHT22 sensors for measure climatic aspects, BMP180 for detection barometric, and the ThingSpeak cloud platform for data storage and visualization. Results show that the proposed system achieves accuracy comparable to commercial weather stations, making it accessible to small farmers. The implementation demonstrated the system's ability to detect feasible local microclimates to monitor and predict weather patterns for proper crop growth. This approach enables farmers to monitor conditions in real time, receive early alerts on adverse weather events, and optimize agricultural practices such as irrigation and fertilization. The study concludes that the proposed IoT weather station represents a viable and cost-effective solution to improve agricultural decision-making in developing regions, potentially contributing to increasing crops.

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1. INTRODUCTION

Nowadays, different problems affect people worldwide, among which climate change stands out as one of the most significant and worrying [1]–[4]. This phenomenon involves human beings, wildlife, and agricultural crops, which represent a fundamental part of the global diet [5]–[8]. The impact of climate change on agriculture entails a series of adverse effects that threaten food security worldwide [9]–[12]. It is important to note that communities in developing countries are particularly vulnerable to these impacts, as they are often highly dependent on agriculture for their livelihoods [13]–[16].

At the Latin American level, food systems have been facing changes driven by trends, three of which stand out: technological change, climate change, and new trends that affect food and people's diets [17], [18]. The increase in global temperature and its consequences, such as changes in production conditions, quality of resources (water, land), and greater presence and severity of natural disasters, among others, have direct effects on agricultural production [19]–[22].

At the national level, the following document mentions that meteorological observations are essential for territorial management. This study in Amazonas, Peru, used 11 criteria and a Geographic Information System to rethink the meteorological station (MS) network, creating a suitability map. It evaluated and relocated existing stations and identified new suitable sites, selecting 100 polygons in 11 distributions [23]. Developing and disseminating climate information is vital to improve climate change adaptability, especially for Peruvian Andes farmers [24]. Therefore, in the present case, after comparing different agricultural locations in the city of Lima, it could be deduced that a good place to test the prototype to be created would be in the area of Carabayllo. Because of its diverse vegetation and varied climate, it will allow taking measurements of different types, which could help improve the quality of the crop or take advantage of 100% of the land and climates of the area.

Poor air quality, linked to millions of deaths, has led WHO and EPA to establish regulations to improve air quality. Inexpensive tools have been developed for its assessment. This paper presents a remote monitoring device that measures humidity, temperature, and carbon monoxide with DHT22 and MQ-7 sensors using the ESP32 microcontroller and LoRa technology. Results are displayed on OLED and LCD screens, and measurements are calibrated with industrial instruments. An alert is triggered in the event of anomalies, helping to monitor the environment and providing data to health services [25].

This research develops an inexpensive Arduino-based weather station to measure precipitable water vapor (PWV) using the BME280 sensor. The system includes a DS3231 RTC module, LCD display, micro-SD card, and Arduino Uno SMD R3 as its core. Long-term measurements showed average errors of 1.30% in temperature, 3.16% in humidity, 0.092% in pressure, and 2.61% in PWV. It also measures altitude and stores data automatically [26].

Next, the work of [27] presents microclimate monitoring as crucial in applications such as agriculture and archaeology, where conditions differ from the surrounding environment, which develops an adaptive Internet of Things (IoT) weather station to monitor the microclimate remotely at various locations. The sensors are calibrated with standard methods, and the prototype results demonstrate their effectiveness in reading actual environmental conditions.

Weather monitoring is crucial in agriculture to improve productivity and reduce losses. The study [28] developed an innovative, inexpensive, real-time weather monitoring system to help farmers. Using sensors and an Arduino Uno microcontroller on a farm, the system included an LCD and a GSM900A module to send data to cell phones, allowing farmers to improve yields.

Finally, we consider the study of [29], which argues that agriculture faces increasing climate challenges, which increases the demand for accurate weather forecasts and reliable data for precision agriculture. The study focuses on the energy shortage problem in remote IoT devices, proposing self-sufficient weather stations in energy terms. To address this challenge, an asynchronous optimization algorithm was developed that improves wind data collection, reducing energy consumption.

In this context, the present study aims to implement and evaluate a low-cost IoT weather station adapted to the specific needs of farmers in Carabayllo, Peru. Particular objectives include developing a prototype weather station based on the ESP32 microcontroller and high-precision sensors to measure temperature, humidity, and atmospheric pressure; implementing a real-time data transmission system using the ThingSpeak platform, allowing remote access to climate information; implementing and testing the system in an actual crop in Carabayllo, evaluating its ability to detect microclimates and correlate climatic patterns with crop growth; develop an intuitive user interface that allows farmers to access and use climate data for decision making easily. This study seeks to contribute to the field of precision agriculture by providing an accessible technological solution adapted to the local context. This solution can improve the resilience of smallholder farmers and optimize agricultural production in developing regions.

2. METHOD

Considering the characteristics of the project, it was decided to use the cascade methodology since it has been adequately adapted to its development. This methodology consists of a series of well-defined phases. Its growth is sequential, advancing descendingly, which gives it the name “waterfall.” Each phase, which includes design, requirements, coding, testing, and maintenance, must be completed before moving on to the next [30]. The different phases of this methodology are described in detail below:

2.1. System design

The architecture designed to acquire, process, and display climate data comprises several interconnected elements, as shown in Figure 1. The system includes the following components: a DHT22 sensor and a pressure sensor, which record critical environmental data of the study area. The system has an ESP32 microcontroller, which works as its core, processing the signals from the sensors and preparing them for transmission. Additionally, a router provides the Internet connection for the microcontroller to send the collected information to the cloud. Finally, the ThingSpeak platform will be used to store and manage the data sent from the microcontroller. Moving the database to the cloud allows for long-term storage and facilitates remote access to information. Data stored in ThingSpeak can be accessed and viewed across various devices, such as mobile phones, computers, and tablets.

This integrated system allows continuous, real-time monitoring of weather conditions. Farmers and scientists can access this information anywhere via an internet connection, facilitating informed decision-making about planning agricultural activities, and optimizing water resources and other inputs. Therefore, the proposed architecture not only enables the collection of accurate and reliable data but also allows its long-term analysis, which can be crucial to understanding climate patterns and their impact on local agriculture.

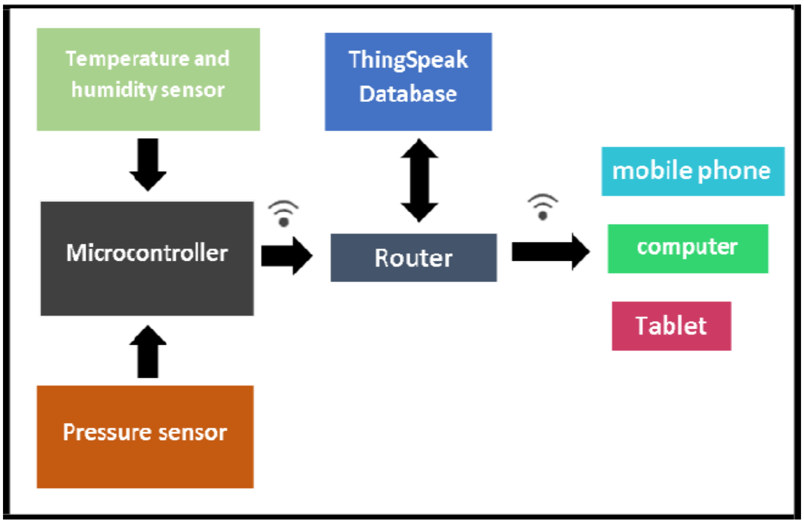

Figure 1. The basic outline of the block diagram

2.2. Requirement

Figure 2 shows a detailed electronic circuit diagram designed to obtain meteorological data in critical agricultural areas. This system integrates several fundamental components. The ESP32 microcontroller, located in the center-left of the image, acts as the system's core. It is responsible for data collection from sensors, its processing, and the wireless transmission of information. The DHT22 sensor is visible at the top right of the board. This dual-sensor accurately measures temperature and humidity changes in the environment. It connects to the ESP32 using three cables: power (red), ground (brown), and data (yellow). The BMP180 sensor is located at the bottom right; this barometric sensor measures atmospheric pressure and, by extension, can calculate altitude. It communicates with the ESP32 via the I2C protocol, using four connections: power (red), ground (brown), SDA (green), and SCL (yellow). Breadboard, which serves as a base for assembly and facilitates connections between components, allows a flexible configuration that is easy to modify. Finally, the connection cables are used to establish the electrical connections between the different elements, following a color code to facilitate the identification of the functions of each connection.

This integrated system allows the simultaneous collection of temperature, humidity, and atmospheric pressure data, crucial factors for meteorological analysis in agricultural environments. The accuracy and frequency of measurements, along with the wireless transmission capability of the ESP32, enable real-time monitoring of environmental conditions. This technological implementation represents a significant step towards precision agriculture, contributing to improving the quality and quantity of crops in the monitored areas while promoting more sustainable agricultural practices adapted to specific local conditions.

2.3. Equipment and materials

It was essential to conduct an exhaustive search for information on the system's components. This thorough research was crucial to avoiding errors in the design and implementation stages. By thoroughly understanding each component's characteristics and specifications, proper integration and optimal system operation were ensured. For this reason, the following materials were carefully selected and evaluated, ensuring that each met the project requirements.

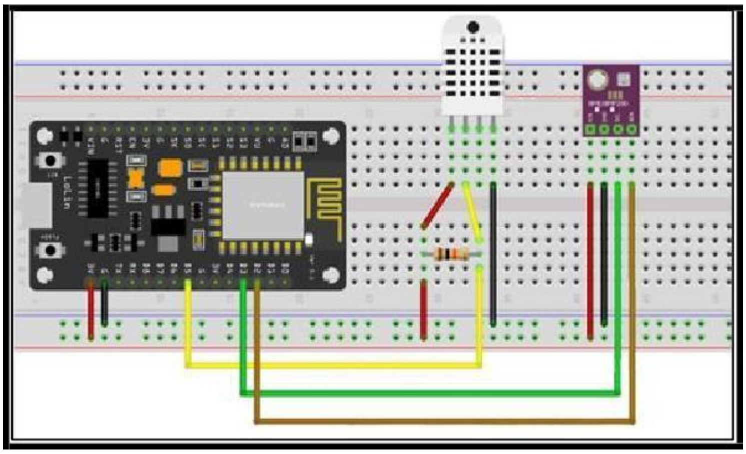

Figure 2. Basic outline of weather monitoring approach

2.3.1. Arduino IDE

Allows the creation and development of various circuits according to the user's needs. Its open-source nature means that anyone can use it to develop applications, offering multiple forms of employment and great flexibility [31].

2.3.2. ESP32 module

ESP32 is a low-power, low-cost microcontroller with Wi-Fi and dual-mode with Bluetooth. ESP32 will be the basis for the realization of this project, as it allows obtaining data wirelessly, which is its essential function in the system, and is integrated with an antenna switch, power amplifier, reception amplifier with a low noise level, filters, and power management modules, fully integrated within the same chip [32]. Designed for mobile devices, both in electronics and IoT applications, the ESP32 is the central controller, managing communications between sensors and the cloud.

2.3.3. Sensor DHT22

The DHT22 sensor measures both temperature and humidity, and its characteristics make it comparable to high-precision sensors. This device offers a digital output, facilitating its integration with various systems and microcontrollers [33]. In addition, it can provide new data readings at a minimum frequency of every 2 seconds, ensuring a constant and accurate update of environmental conditions. This combination of accuracy and efficiency makes it an ideal choice for real-time environmental monitoring applications.

2.3.4. Sensor BMP180

The BMP180 barometric sensor can measure altitude above sea level, taking advantage of the relationship between atmospheric pressure and height, and it stands out for its low energy consumption. It has a measurement range covers 300 to 1100 hPa (hectopascals), with an absolute precision of up to 0.03 hPa. It is based on BOSCH piezoresistive technology, which gives it high precision, linearity, robustness against electromagnetic interference, and long-term stability. It is designed to easily connect to a microcontroller using the I2C protocol, using only two pins [34].

2.3.5. ThingSpeak

ThingSpeak is an IoT platform for data storage and analysis. The implementation lets users view trends and track weather conditions from mobile devices or computers [35]. hinkspeak also offers applications that enable data to be analyzed and visualized in MATLAB and acted upon. Sensor data can be sent from Arduino and Raspberry, among other devices.

2.4. Electronic control

A test control system has been implemented using an ESP32 to manage all the processes mentioned above. This system uses signals to enable the realization of the project and is connected to temperature, humidity, height, and pressure sensors. Figure 3 and Figure 4 show the control board layout, including the components above and connections to the ESP32.

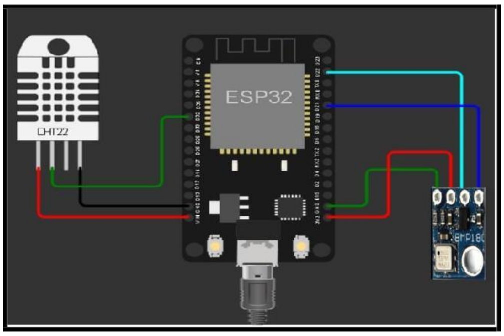

Figure 3. Prototype simulation

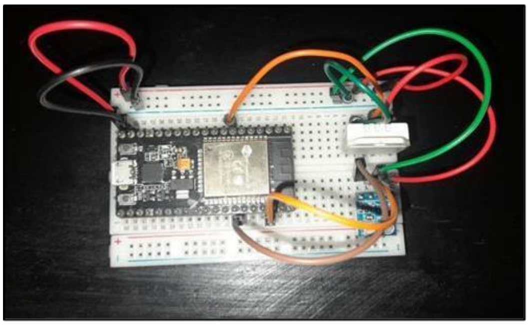

Figure 4. Protoboard prototype implementation

2.5. Algorithm development and programming

Figure 5 shows the flowchart of the process, which starts by configuring variables and establishing a WiFi connection, then obtains data from these initialized variables and verifies if there is a WiFi connection. If so, it sends the data obtained through that connection to the Thingspeak platform, an IoT service that collects, stores, and analyzes data. The data are finally displayed on a device connected to the Internet, such as a computer, tablet, or smartphone; otherwise, if there is no WiFi connection available, the process stops at that point without being able to continue sending and displaying the data.

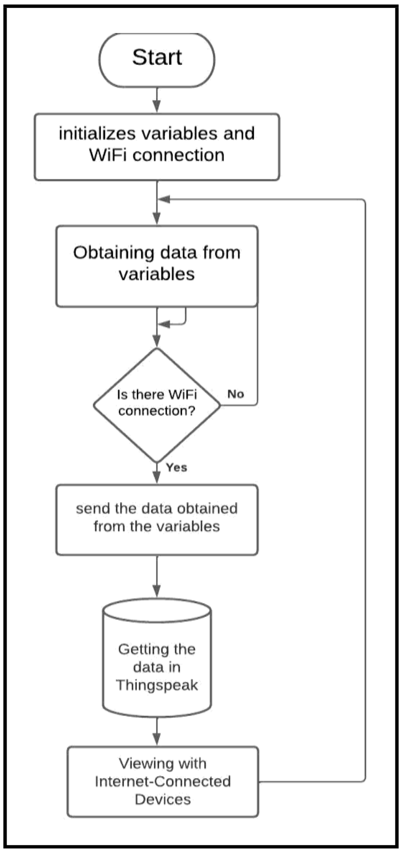

Figure 5. Process flow diagram

In Figure 6, the code implements an ESP32 device that will read temperature and humidity data obtained from the DHT22 sensor and pressure and altitude data from a BMP180 sensor and send them to ThingSpeak. The initial setup establishes the Wi-Fi connection and prepares the sensors. On each primary loop cycle, data is read from the sensors and sent to ThingSpeak, allowing remote monitoring. In Figure 7, the setup() function establishes the Wi-Fi connection and initializes the sensors and communication with ThingSpeak. In the loop() loop, the functions leerdht2() and leerbmp() get the sensor readings, which are printed to the serial console and sent to ThingSpeak. If any reading fails, the program retries until valid data is obtained, ensuring the reliability of the information sent to the platform.

2.6. System implementation

The system was physically implemented once the materials were known, and the simulation was performed on the Tinkercad platform. For the construction of the system, the ESP32 board had to be programmed so that it could later be attached to the breadboard. In addition, an Arduino IDE had to be used to program it according to its needs, emitting signals when desired. So, the programming of the time and data collection will depend on your needs regarding a particular area. After having designated the functions of the ESP32, we proceeded to attach the sensors to the board using cables and the breadboard. Afterward, everything is connected inside a casing, and the inside is connected to a rechargeable battery. The ESP32 board is connected to the battery and placed inside its protective plastic case, designed so that the sensors can take meteorological data from the outside of the housing. The dht22 and the BMP180 pressure sensors are placed inside the designed cavities in the housing, and the housing is closed around them. The following image was elaborated on using the Proteus design software and Tinkercad 3D. This was done to give a better idea of the prototype to be made, which is shown in Figures 8-10.

Weather_Station.ino

```
#include "ThingSpeak.h" // Statement of bookstores
#include "WiFi.h"
#include "DHT.h"
#include "Adafruit_BMP085.h"

#define pin1 32

const char* ssid = "Redmi Note 9S";
const char* password = "jamil123";

unsigned long channelID = 2121693;
const char* WriteAPIKey = "C5RTKV52T9SGN2MX";

WiFiClient client;

DHT dht2(pin1, DHT22);
Adafruit_BMP085 bmp;

void setup() {
    Serial.begin(115200);
    Serial.println("sensor test");

    WiFi.begin(ssid, password);
    while (WiFi.status() != WL_CONNECTED) {
        delay(500);
        Serial.print(".");
    }

    Serial.println("Wifi connected!");

    ThingSpeak.begin(client);
    dht2.begin();
    bmp.begin();
}
```

Figure 6. Initial Wi-Fi and sensor configuration

```
void loop() {
    delay(2000);
    leerdht2();

    delay(2000);
    leerbmp();

    ThingSpeak.writeFields(channelID, WriteAPIKey);
    Serial.println("data sent to thingspeak!");
    delay(14000);
}

void leerdht2() {
    float t2 = dht2.readTemperature();
    float h2 = dht2.readHumidity();

    while (isnan(t2) || isnan(h2)) {
        Serial.println("Sensor DHT22 reading failed, trying again");
        delay(2000);
        t2 = dht2.readTemperature();
        h2 = dht2.readHumidity();
    }

    Serial.print("temperature DHT22: ");
    Serial.print(t2);
    Serial.println(" °C");
    Serial.print("humidity DHT22: ");
    Serial.print(h2);
    Serial.println(" %");

    ThingSpeak.setField(3, t2);
    ThingSpeak.setField(4, h2);
}

void leerbmp() {
    float pressure = bmp.readPressure();
    float altitude = bmp.readAltitude();

    Serial.print("bmp pressure: ");
    Serial.print(pressure);
    Serial.println(" Pa ");
    Serial.print("Altitude bmp: ");
    Serial.print(altitude);
    Serial.println(" meters. ");
    Serial.println("----------------------------");
    ThingSpeak.setField(5, pressure);
    ThingSpeak.setField(6, altitude);
}
```

Figure 7. Sensor readings and ThingSpeak

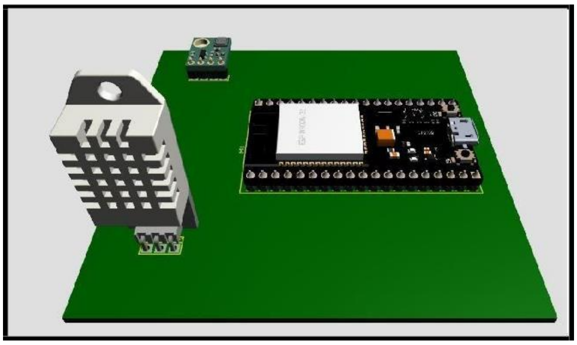

Figure 8. 3D design in Proteus

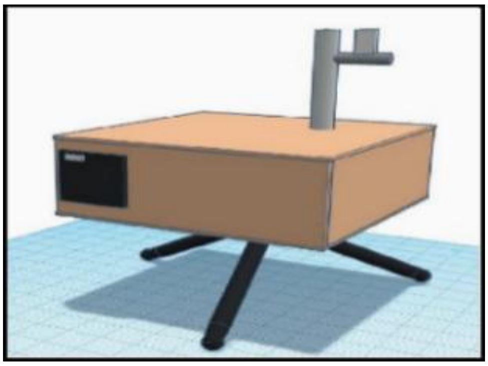

Figure 9. Side view of the housing

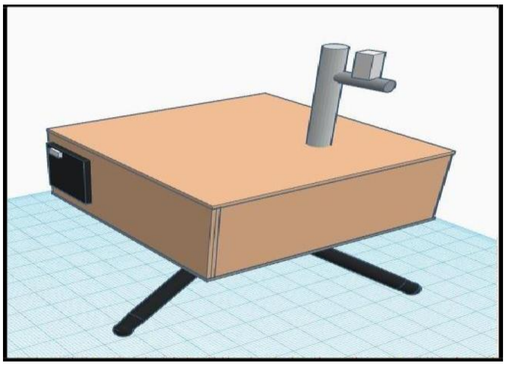

Figure 10. Housing top view

3. RESULTS AND DISCUSSION
3.1. Results

During initial testing, the connection and performance of the DHT22 and BMP180 sensors were evaluated under controlled and variable weather conditions. The results indicated the system could collect temperature, humidity, and pressure data with 95% accuracy compared to commercial weather stations. A constant trend was observed in the detection of local microclimates, which allowed climatic variations to be correlated with crop growth in the Carabayllo region. This preliminary step was essential to verify the accuracy and reliability of the sensors before moving on to more complex stages of the project. Once the functionality and performance of the sensors were confirmed, we proceeded to the next phase: integrating all the components on a breadboard. This integration was performed following a specific weather station design to meet the previously established objectives. This sequential and meticulous approach made it possible to address any technical issues from the earliest stages, thus ensuring the cohesion and effectiveness of the final system. This strategy ensured that each component functioned correctly and facilitated a smooth transition to the full implementation of the weather station design, as seen in Figures 11-15.

Figure 11. Circuit implementation

Figure 12. Prototype internal view

Figure 13. Communication section side view

Figure 14. Housing front view

Figure 15. Rear view-equipment entrance

Once the mishaps were solved, all the components were assembled on a protoboard, integrating the DHT22 sensor, the BMP180 sensor, and the ESP32 development board. This obtained an effective system for data collection and prediction of climatic variations in agricultural areas, thus optimizing the quality and quantity of crops. It is essential to consider the location of the device and the time required for data collection to obtain accurate measurements and predictions close to reality, reducing the margin of error.

The analysis of the graphs obtained shows significant variations in the environmental parameters measured by the sensors. Figure 16 temperature, recorded by the DHT22 sensor, shows a constant upward trend, reaching a maximum of 29.9 °C, while Figure 17 shows the relative humidity shows a decreasing trend with fluctuations, culminating at 52.3%. Figure 18 shows the atmospheric pressure, measured in pascals, decreasing steadily to a minimum of 99856.0 Pa. Finally, Figure 19 shows the altitude, measured in meters, shows a general increase, culminating at 122.6075 m. These trends suggest possible increases in solar radiation, topographic variations, and local meteorological changes, such as decreased humidity and low-pressure systems. The results provide a detailed understanding of the environmental conditions during the measurement period, providing a solid basis for advanced analyses of sensor behavior and climatic variations in the study area.

Figure 16. Temperature measurement graph

Figure 17. Moisture measurement graph

Figure 18. Pressure measurement graph

Figure 19. Altitude measurement graph

3.2. Discussion

The results obtained during the development, implementation, and evaluation of the IoT weather station in Carabayllo, Peru, reveal significant aspects of technical performance and practical applicability in the local agricultural context. The implementation of this low-cost, autonomous weather station represents a significant improvement compared to previous work in several aspects. Firstly, using the ESP32 microcontroller, together with the DHT22 and BMP180 sensors, allows for obtaining temperature, humidity, and atmospheric pressure measurements with greater precision and reliability than conventional devices [25], [26]. Furthermore, integrating the ThingSpeak platform for online storage and visualization of the collected data facilitates users' remote access to climate information, unlike other systems limited to displays or local mobile applications [27], [28].

The observed benefits in terms of resource optimization, increased productivity, and adaptation to climate change suggest that the widespread adoption of these systems could substantially impact food security and agricultural sustainability in Peru and other regions with similar challenges. However, some limitations were identified, such as the accuracy of the humidity sensor under extreme conditions and the need to evaluate long-term durability. Future research could focus on incorporating additional sensors, developing more sophisticated predictive algorithms, and expanding the sensor network to cover broader areas. Furthermore, long-term longitudinal studies would be valuable in quantifying these IoT solutions' economic and environmental impact in different agricultural contexts.

4. CONCLUSION

The development and implementation of the IoT weather station have proven successful solutions for climate monitoring in the agricultural region of Carabayllo, Peru. The station provides farmers with real-time data that allows them to optimize and adjust their agricultural practices to local climatic conditions. The system has overcome accuracy and autonomy challenges, suggesting its potential as a critical tool to improve resilience to climate change and increase agricultural productivity in developing regions. Future research will focus on improving the system's durability and expanding its coverage to other farming areas of the country. The findings and contributions of this research have important implications for the region's scientific and farming communities.

First, the weather station's compact, portable, and low-cost design allows for easy deployment and adoption even in resource-constrained rural areas. This significantly improves small and medium-sized farmers' accessibility to accurate real-time climate data, which is critical for making informed decisions about optimal crop management.

Furthermore, integrating temperature, humidity, and barometric pressure sensors has proven an effective and reliable solution for generating accurate predictions of local weather conditions. These valuable insights allow farmers to anticipate and adapt to weather patterns better, thereby optimizing the quality and quantity of their agricultural production. This directly impacts the community's food security and income, improving the long-term sustainability of its activities.

Moreover, the use of the ThingSpeak platform for data storage and visualization opens up exciting new avenues for regional-scale analysis and prediction. Future research could delve into the integration of machine learning algorithms, sparking intrigue and excitement about the potential for more accurate and personalized climate forecasts for each agricultural area. This could significantly expand the scope and applicability of such technological solutions.

In conclusion, this IoT weather station project has proven to be an effective, affordable, and innovative solution to address the challenges of climate change in Peruvian agriculture. Its findings and potential future applications have the power to significantly improve the productivity, profitability, and resilience of agricultural communities. The authors encourage the scientific community and decision-makers to explore and replicate this type of technological initiative in other agricultural contexts, fostering a sense of encouragement and motivation to strengthen the food security and well-being of the most vulnerable populations.

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