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Sustainability of precision agriculture as a proposal for the development of autonomous crops using IoT

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ABSTRACT -Agricultural activities have experienced a significant increase due to population growth; hence, the demand for food has risen to the point where prioritizing greater efficiency and quality in crop production within a short period is crucial. This paper addresses the contemporary need to design prototypes focused on optimizing natural resources, specifically in the agricultural sector, where recurring wastage of water, fertilizers, and pesticides is evident. This research proposes a comprehensive prototype incorporating a monitoring and control system managed through the IoT Arduino Cloud platform using an ESP32 development board to improve resource management from the initial germination stages to harvest. The planting phase is based on a 3D printer mechanism with three-dimensional movements controlled. The monitoring system includes real-time visualization of variables such as temperature, soil humidity, and electrical magnitudes, as well as the automation of the irrigation and fertilization system. In this regard, the results demonstrated efficient resource management in cultivation. Additionally, the photovoltaic system contributes to a more sustainable and efficient management approach.

Keywords: Cultivation; Germination; Population growth; Statistical analysis; Internet of things

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1. INTRODUCTION

In recent years, various research groups have thoroughly examined the impact of integrating robotics in agriculture, primarily focusing on activities related to controlling and monitoring crops. The automation of tasks performed by these robots includes activities such as pest detection, planting, irrigation, and fertilization, transforming cultivation from static to dynamic and intelligent [1]. Precision agriculture has evolved to enhance crop quality and shorten production times. Additionally, implementing new technologies in the agricultural sector is essential for optimizing natural, economic, and industrial resource management [2].

Autonomous aerial and ground robot development has the minimum capabilities required to perform monitoring and control activities. One project related to this theme is the RHEA project developed by Angela R., which involves a multi-robot system performing ground and aerial movements to collect crop information. The gathered data is transmitted to a control center through a wireless sensor network using communication protocols such as MQTT and HTTP, along with the Internet of Things (IoT) [2]-[3]. Creating a database is crucial for making informed decisions through analysis and interpretation, aiming to increase the quantity and quality of crop production [4]. Another project by Thomopoulos V. utilizes these robots for data collection through IoT in hydroponic crops, employing spectroscopy for real-time crop monitoring [5].

The application of IoT in precision agriculture stands out for its ability to efficiently collect and store data in the cloud from various sensors distributed in the field [6]. This data is fundamental for evaluating and creating models based on Artificial Intelligence (AI) and implementing automated systems [7]. Through these systems, the user (farmer) can monitor and analyze critical variables directly affecting the crop, such as temperature, humidity, soil moisture, pH levels, and atmospheric pressure [8]-[9]. Furthermore, IoT finds applications in management systems for warehouses, livestock, irrigation, agricultural vehicles, and waste, among others. Monitoring and collecting data on crop conditions enable the development of algorithms for more efficient resource management [10]-[11].

In this context, the advancement of Information and Communication Technologies (ICT) plays a fundamental role, allowing for easy adaptation of sensors, development boards, and cloud storage, facilitating data collection and storage for subsequent analysis [12]. Integrating Artificial Intelligence (AI) in precision agriculture also plays a crucial role in enabling more precise and cost-effective resource management [13]. The detection of diseases through artificial vision is one of the areas where extensive research has been conducted, allowing the evaluation of various parameters through image processing, primarily assessing the presence of insects and pathogens causing diseases in crops [14].

The creation of prototypes of autonomous robots driven by AI algorithms becomes increasingly crucial in the field of precision agriculture. These robots can perform specific actions and make decisions based on the surrounding situation and environment. Among the various tasks they perform are monitoring, fertilization, and unwanted vegetation removal in crops, all thanks to the application of artificial vision. Regarding navigation, prototypes use Mission Planner software to follow specific routes through GPS navigation systems [15]. Another method for positioning robots in the field is using LIDAR sensors to detect obstacles and enable efficient evasion [16].

The use of Wireless Sensor Networks (WSN) has experienced significant growth in agriculture, with notable applications in remote monitoring of environmental conditions, soil, and crops [17]-[1]. The need for individual fields and crops is observed and analyzed through this data, specifying the distribution of resource quantities used in control systems for monitoring moisture, fertilization, and disease detection. This approach increases crop yield and profitability [14]-[18]. Several studies have proposed IoT-based monitoring systems to visualize and collect data in this area, optimizing water usage in agricultural irrigation systems [19]-[20].

The main parameters for implementing AI in autonomous crops are accuracy, sensitivity, precision, and specificity. These systems are commonly implemented on development boards such as Raspberry Pi, ESP32, and Arduino [21]. These devices receive information from sensors for processing, analysis, and decision-making. They are also responsible for notifying the user (farmer) about the crop's status through an interface displaying all relevant variables [22]. Efficient crop monitoring through an interface enables comprehensive monitoring and control automation for crops in remote locations. This approach significantly optimizes the growth process until product harvest [23]. Are presented.

This present document is organized as follows: in Section, I, an introduction and the state of the art related to the topic are presented; in Section II, related works are discussed; in Section III, information about the proposed work is presented; in Section IV, the hardware and software of the designed system are outlined; in Section V, the results obtained are displayed and discussed. Finally, in Section VI, the main conclusions and recommendations are presented.

2. RELATED WORK

Monitoring soil conditions, climatological variables, and resource management poses a significant challenge in precision agriculture. Article [14] utilizes IoT for data collection and storage through sensors installed at various points on a farm. This allows for a deep analysis of the system to create an AI-based algorithm that controls natural resource management, primarily disease detection. The results showed that it is possible to detect diseases based on the state of the crop leaves. Articles [22]-[5] leverage IoT for continuous crop monitoring. This system alerts the user through alarms if any variable falls outside the predefined normal range. Additionally, this data is stored in the cloud, enabling analysis that contributes to the continuous improvement of the agricultural process.

In article [19], a scalable wireless sensor network architecture for monitoring and control, using IoT for agriculture in a remote area, is presented to enhance farmers' productivity. This sensor network is based on WSN technology, maximizing performance and minimizing latency and signal-to-noise ratio. The research results demonstrated that supervised systems can quickly improve agriculture and livestock performance. Articles [1]-[17] also utilize this IoT and sensor network architecture to collect data in the cloud for implementing deep learning algorithms in autonomous crops.

3. PROPOSED WORK

Developing prototypes focused on optimizing natural resources is necessary, especially in the agricultural sector, where water, fertilizers, and pesticides are wasted. In this context, introducing monitoring and control systems through IoT emerges as a critical solution to enhance resource management from the early stages of germination to the harvest phase. This innovation simplifies and stimulates the progress of autonomous and intelligent agricultural initiatives [14].

The following proposal for an innovative prototype is presented based on conclusions drawn from various sources. It comprises two fundamental elements: a planting system and a monitoring system using IoT technology through Arduino Cloud. The prototype's structure consists of a small greenhouse with a one-square-meter area specifically designed for cultivating six bean plants. The design of the planting system is based on the movement of a 3D printer operating on three axes (x, y, z), housing actuators responsible for longitudinal and transversal movements on these axes. For control, a semi-automatic ML-based system is proposed, responsible for locating the given coordinates for seed planting.

The monitoring system receives signals from sensors and controls crop fertilization and irrigation. Two longitudinal carts move along the crop for this purpose. This system is managed by an ESP32 board, which connects to strategically distributed sensors for data collection. Through signals emitted by these sensors, the ESP32 board coordinates actions to maintain temperature, soil humidity, and fertilization levels at optimal levels for crop development. It is essential to highlight that these systems are controlled manually and automatically, constantly supervised through the IoT interface by the user. This ensures comprehensive real-time monitoring for informed decision-making.

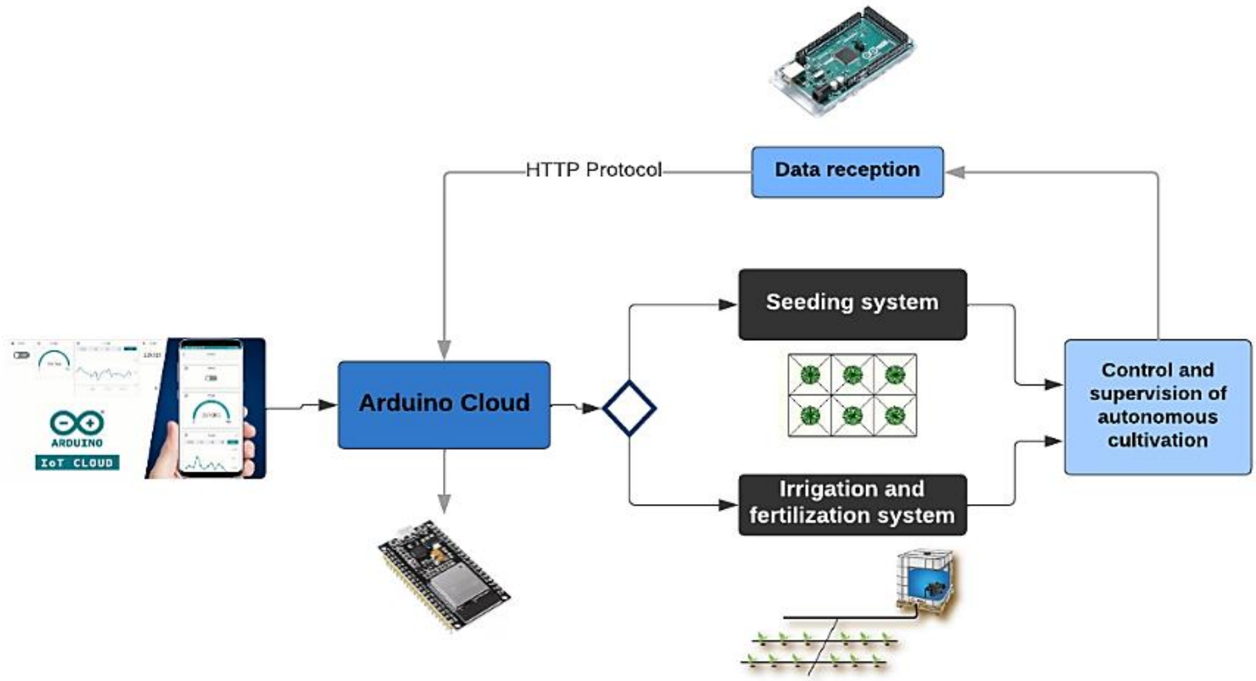


Figure 1. IoT architecture layer proposed in prototype

3.1. Proposed System Hardware and Software

The proposed prototype in the text is characterized by a comprehensive combination of hardware and software, leveraging IoT technology through Arduino Cloud to achieve efficient and autonomous management in agricultural cultivation. The contribution of both components in this system is detailed below:

3.2. Hardware

The proposed autonomous cultivation system is used for monitoring and control, considering the following parameters:

- Photovoltaic power generation system of 50 W and 12 V.
- Control of the autonomous cultivation system via IoT or local.
- Monitoring electrical variables and the crop environment's physical magnitudes in real time on a PC or mobile device.
- Data storage in the cloud.
- Sowing and fertilization positioning system.
- Recording of values through sensors installed in the crop.

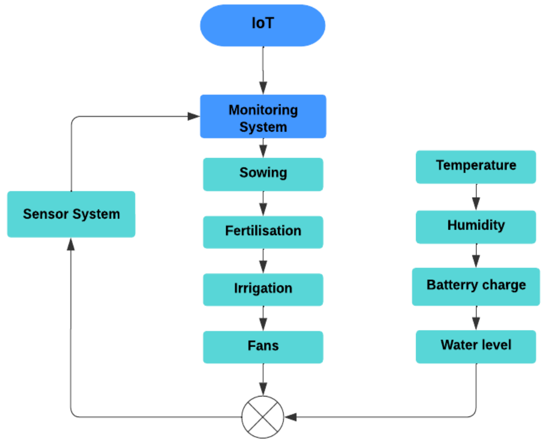


Figure 2. Diagram of the autonomous cultivation system.

Figure 2 illustrates the general block diagram of the proposed design architecture for the Autonomous Crop (CA). It visualizes those sensors installed in the crop send information to the IoT system, allowing the designed control system to make decisions based on the state of the measured variables. These data are also displayed on the monitoring interface for the user to oversee crop conditions.

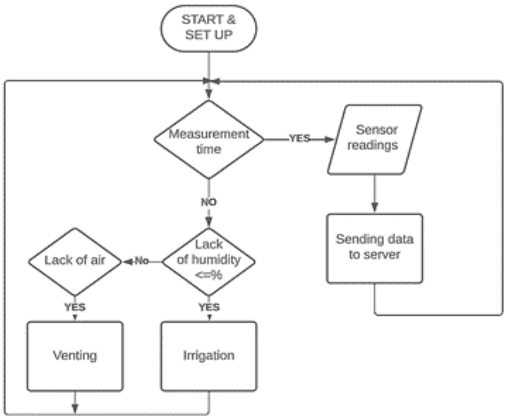


Figure 3. Monitoring and control system block diagram

Figure 3 illustrates the key stages and component interconnection in the designed system for monitoring and controlling soil variables. Sensors collect environmental data, focusing on soil moisture and fertilization levels. The control system processes and analyzes this data through the designed control algorithm, facilitating decision-making. Actuators automatically respond to the needs identified in the crop. All historical records are stored in the cloud, providing a comprehensive database for system configuration and monitoring.

Data acquisition utilized an Arduino Mega 2560 board connected to the sensors responsible for sending signals for autonomous crop control and monitoring. An ESP32 control board was also used to transmit data, including soil moisture percentage, temperature, and fertilization level measurements from the cultivation area. This data is sent via its WiFi module to the Arduino Cloud IoT platform, triggering control signals for planting.

The ESP32 development board manages multiple processes simultaneously in this prototype. It controls stepper motors using an ML-based algorithm, monitors soil temperature and humidity, regulates crop irrigation, manages fertilization, and facilitates power supply through the photovoltaic system. Additionally, it serves as the master controller, sending commands to the autonomous planting system and contributing to comprehensive and efficient agricultural operations management.

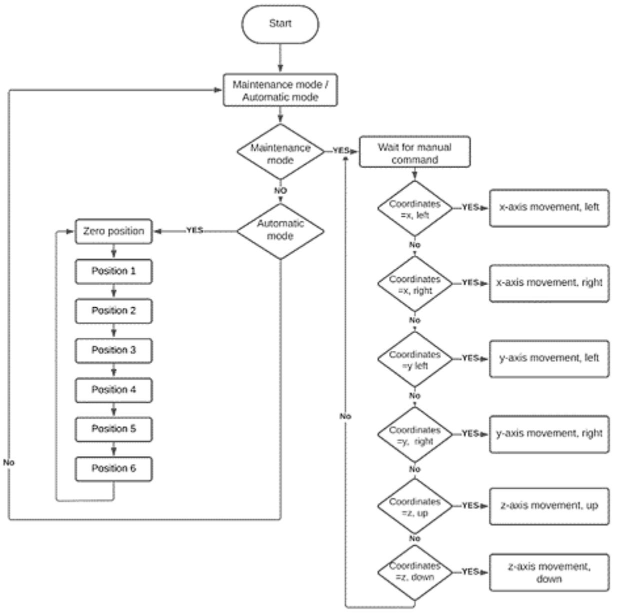


Figure 4. Block diagram of the seeding system

In *figure 4*, the planting system is observed, equipped with three stepper motors used for seeding. These actuators generate movement along the axes (x, y, z) to position the system at six user-defined points on the terrain. The system drills and places the seed at a depth of 1cm, initiating the germination process for the bean seed. This planting process takes an estimated time of 60 seconds.

3.3 Software

The construction of the prototype of the autonomous agricultural system consists of three methods: the planting system uses a Ramps 1.4 board that, together with the Arduino Mega board, controls three stepper motors in the three axes (X, Y, Z) that generate the movement for the desired location on the land. The control system that serves is used to control the fertilization schedule, humidity, and temperature inside the greenhouse. The monitoring and data acquisition system uses an ESP32 card to transmit data through its WiFi module to the IoT platform, where real-time control is performed remotely in manual or automatic mode.

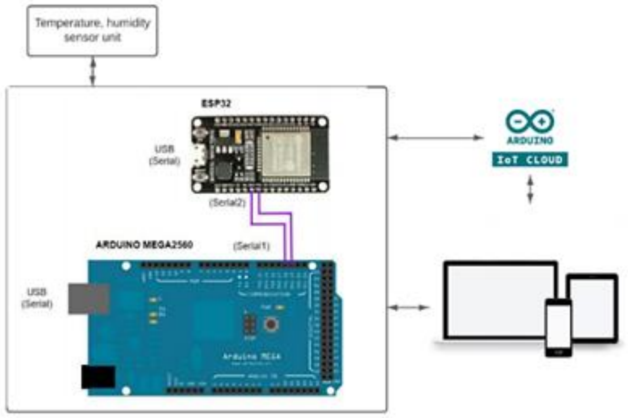


Figure 5. Diagram of autonomous control of variables through IoT

Figure. 5 shows how the programming between the prototype and the Arduino IoT Cloud platform is constituted globally. Initially, functions, libraries, and device identification are declared. The IoT connection loop is performed using the Thing Properties function. The sensors installed inside the greenhouse generate the data transmitted to the server via the MQTT protocol; the data visualization is instantaneous on the web and smartphones.

The estimation of solar radiation for the design of the photovoltaic system was carried out with the help of SOLARGIS software, which provides the necessary calculations for projects that use photovoltaic systems as energy sources and provides documents in PDF format, indicating more specific details that are included. Being a small-scale prototype, the data obtained are comparable to those offered by the software, allowing us to make the necessary comparisons concerning the required calculations. This software was used in the town of Rumiñahui to perform the photovoltaic design and operate more sustainably and efficiently, helping optimize power generation, system performance optimization, battery charge management, and integration with other system components.

4. RESULTS

This section shows the main results obtained from the tests performed on the control system, monitoring, mechanized systems, electronic components, and photovoltaic systems.

4.1 Photovoltaic system

The operation of this system was verified with the help of measurement tools such as voltmeters, ammeters, and sensors that allow us to see different results and contrast them, one concerning another, and then verify these values with the IoT system. Table 1 shows the voltage, current, and electrical power data over 24 hours; these values were recorded on the IoT platform through the FZ0430 and ACS712 sensors.

Table 1. Data of electrical quantities in a stand-alone system

Hour	Voltage [V]	Current [A]	Power[W]
0:00:00	12,40	0,30	3,72
1:00:00	12,35	0,30	3,71
2:00:00	12,35	0,30	3,71
3:00:00	12,35	0,30	3,71
4:00:00	12,35	0,30	3,71
5:00:00	12,25	0,30	3,68
6:00:00	12,25	0,30	3,68
7:00:00	12,25	0,30	3,68
8:00:00	12,30	0,35	4,31
9:00:00	12,30	0,35	4,31
10:00:00	12,30	0,35	4,31
11:00:00	12,65	0,35	4,43
12:00:00	12,85	0,30	3,86
13:00:00	13,00	0,30	3,90
14:00:00	13,20	1,20	15,84
15:00:00	13,45	0,85	11,43
16:00:00	13,60	0,85	11,56
17:00:00	13,40	1,40	18,76
18:00:00	13,20	0,35	4,62
19:00:00	13,00	35,00	455,00
20:00:00	12,80	0,30	3,84
21:00:00	12,60	0,30	3,78
22:00:00	12,60	0,30	3,78
23:00:00	12,45	0,30	3,74

Figure 6 shows the maximum and minimum current, voltage, and electrical power the prototype consumes. These data were taken on a partially cloudy day to verify the systems' correct operation. Figure 6 shows that the maximum voltage reached is 13.6 V DC, a minimum voltage of 12.25 V DC, and an average voltage of 12.6 V DC. For the current, a maximum current value of 1.4 A, a minimum of 0.3 A, and an average of 0.43 A was recorded. Finally, the electrical power consumed was calculated from these two magnitudes, resulting in the maximum power value of 18.76 W, the lowest value of 3.67 W, and an average of 5.56 W.

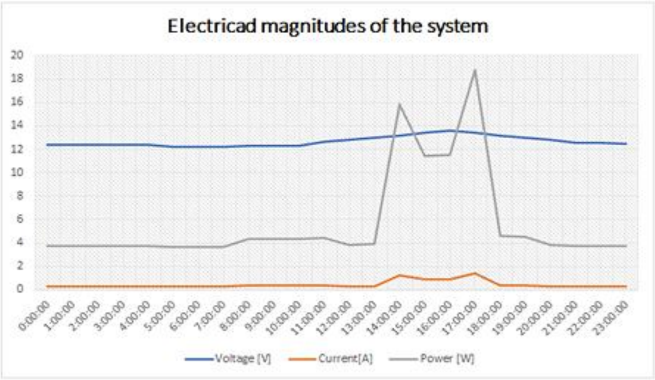


Figure 6. Electrical magnitude data of the system

4.2 Agricultural crop temperature control

With the sole objective of keeping the crop in ideal conditions and not exceeding the maximum value of 27°C, a DH22 temperature sensor was used to control the temperature standards that must be maintained inside the greenhouse to avoid damage to the crop. For this purpose, an ESP32 control card was used to implement an ON-OFF control to turn the fans on and off as a result of the data sent by the sensor. *Table 2* shows the behaviour of these two variables.

Table 2. Soil moisture data

Hour	Temperature (°C)	Humidity (%)
0:00:00	14,2	61
1:00:00	14,2	61
2:00:00	14	61
3:00:00	13,9	61
4:00:00	13,4	60
5:00:00	13,4	60
6:00:00	14,5	60
7:00:00	12,5	60
8:00:00	13,4	60
9:00:00	13,4	59
10:00:00	16	58
11:00:00	22	55
12:00:00	24,1	52
13:00:00	22	48
14:00:00	20	39
15:00:00	19	41
16:00:00	19	45
17:00:00	19	48
18:00:00	15	49
19:00:00	14,9	56
20:00:00	15	61
21:00:00	14,9	61
22:00:00	14,9	61
23:00:00	14,5	61

Figure 7 shows the behavior of the temperature inside the greenhouse, where it can be seen that there are no temperature peaks that could affect the planting. The maximum temperature recorded was 24°C, a minimum temperature of 12°C and an average temperature of 16°C, which is adequate for the crop.

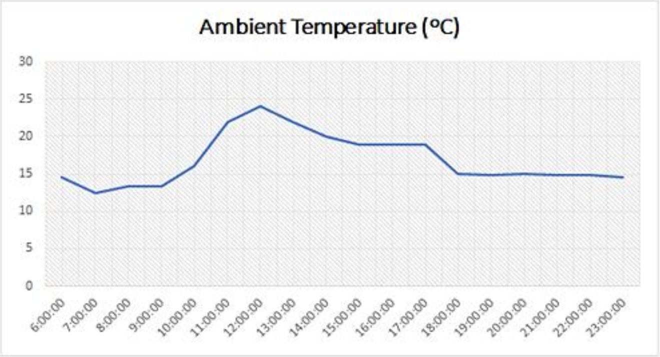


Figure 7. Temperature data inside the greenhouse

4.3 Soil moisture control of crops

Humidity control is essential for cultivation since this system can nourish the plant with everything necessary for its development. The data is recorded through a type 0193 capacitive sensor to control soil humidity, essential for developing the bean crop. This sensor sends the data to the ESP32 control board, which activates a solenoid valve and starts drip irrigation to maintain soil moisture levels above 40.

Figure 8 shows the behaviour of humidity in the crop, where a maximum value of 61%, a minimum value of 39%, and an average of 55.8% are recorded.

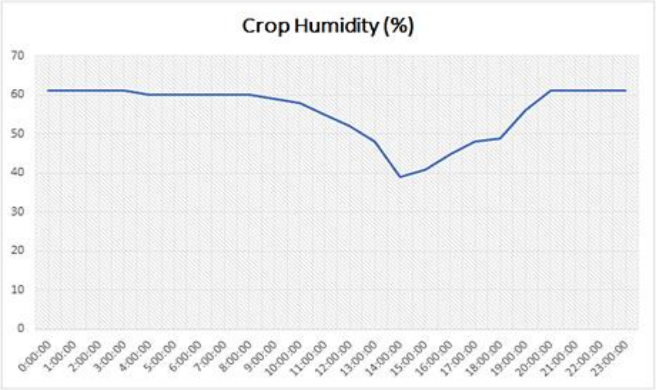


Figure 8. Statistical data of soil moisture value of the prototype

4.4 Control of the fertilization system

Once the fertilization system is integrated into the prototype, tests and adjustments are made to improve its performance. This system uses a NEMA motor, an Arduino development board, an IoT platform to generate a linear mechanical movement, and a water pump to perform fertilization. Adjustments in the mechanical component of the system and the driver to control the motor and programming to ensure a proper connection with the platform through the ESP32.

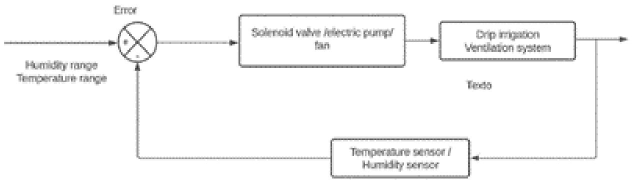


Figure 8. Prototype irrigation and ventilation control system

4.5 Data Discovery

Currently, statistical methods are used to the data. To determine the associations between the input variables, data modeling was employed. Data from *figure 9* offer a clear visual overview of the temperature and humidity data, making them useful tools in precision agriculture. By allowing farmers and agricultural specialists to evaluate environmental variable central tendency, spread, and possible outliers, they facilitate well-informed decision-making for optimal crop management and yield enhancement.

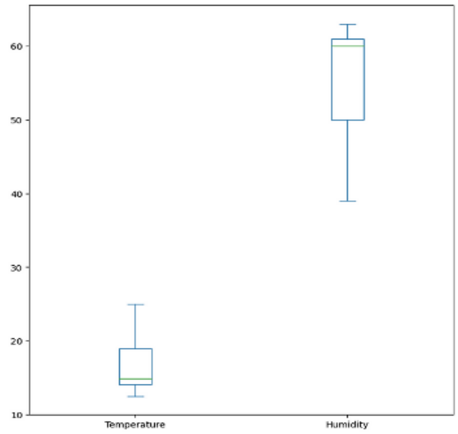
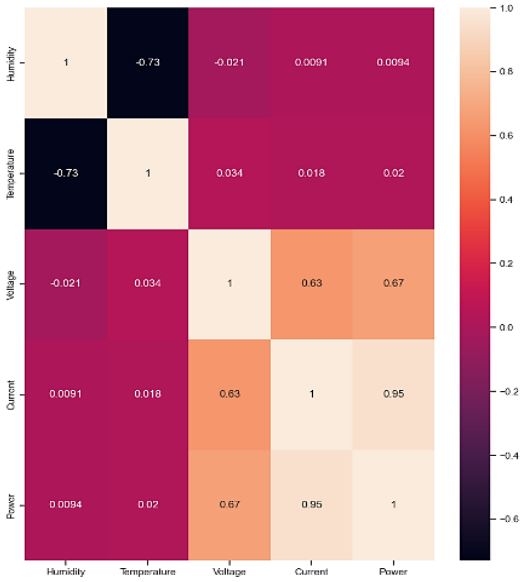


Figure 9. Box-and-whisker plots from temperature and humidity

Figure 10 illustrates the understanding the relationship between temperature, humidity, current, voltage, and power in a smart farming system is essential for comprehending how electrical and environmental factors interact to affect the crop. We can evaluate the strength of the linear relationship between these variables by using statistical methods like correlation analysis. The correlation matrix offers significant information for enhancing the conditions within the intelligent cultivation system by revealing how changes in one variable correspond to changes in another.



	Humidity	Temperature	Voltage	Current	Power
Humidity	1	-0.73	-0.021	0.0091	0.0094
Temperature	-0.73	1	0.034	0.018	0.02
Voltage	-0.021	0.034	1	0.63	0.67
Current	0.0091	0.018	0.63	1	0.95
Power	0.0094	0.02	0.67	0.95	1

Figure 10. Correlation between variables

5. DISCUSSION

The development of the prototype of the autonomous cultivation system shows that the sowing system is composed of a 3-axis movement system for the positioning and perforation of the furrow where the seed will be placed. The area of land where the experiment was conducted is Cuadrado, in which six perforations were made. The estimated time it takes to drill and place the seed is 5 seconds, and the transfer to the next point is

3 seconds. The total time the seeding system takes to perform the seeding is 50 seconds from the zero-position configured by default [14].

The seeding, irrigation, and fertilization system is controlled manually and remotely via Arduino Cloud. These systems use a 50W photovoltaic system at 12 V for the electrical consumption of the motors, development boards, and sensors, whose daily energy demand is 110W. This system also has a 15Ah battery to meet the electrical demand, mainly at night when there is no solar radiation and on partially cloudy days.

The bean crop needs to be kept at a temperature of 15°C to 27°C; for this, an ON-OFF control is performed so that the temperature does not exceed the maximum value of 27°C during the day and does not drop more than 15°C in the early morning hours, through a DH22 temperature sensor the information is collected to control the temperature and humidity (60%-70%) that allow an ideal development of the crop inside the greenhouse to avoid damage and diseases. Arduino iCloud enables the monitoring of these variables and control over time. The tests carried out in the three months show that the growth of the bean crop compared to a traditional crop is more beneficial because the harvest time is shortened. Thus, it is essential to have an automated system to carry out the irrigation and fertilization processes.

The main findings can be summarized as follows: precision agriculture allows more accurate management of resources, such as water and fertilizers, due to knowing the exact needs of each field area. With a network of IoT-based sensors, it is possible to monitor soil conditions in real-time and adjust soil quality to avoid pests and diseases.

The present results also support the findings obtained by Khoa et al. in their work [18], where they proved the effectiveness of a general sensor network for monitoring and controlling variables with the help of the Internet of Things.

For future work, it is proposed to implement an autonomous crop in a larger area, where more variables are available, and the process from germination to crop harvesting is studied in detail. For this, it is essential to integrate artificial intelligence to detect diseases in the crop using synthetic vision. The proposed prototype can help farmers detect and eradicate diseases in time to avoid crop losses.

6. CONCLUSIONS

The control and monitoring of the crop helped to shorten harvesting times, thus reducing the consumption of resources, and optimizing the irrigation system, avoiding unnecessary waste of water resources. This is thanks to the integration of IoT, which allows remote control and monitoring.

The findings of this study indicate that the average soil moisture percentage, corresponding to 55.8%, provides critical information on soil conditions and reveals a trend in cloudy days, which in turn has significant implications on crop health and yield.

The current findings also add to a growing body of literature on precision agriculture, where the focus is on recording data for statistical analysis, accurate responses to weather conditions, planting crops, and applying inputs more appropriately, impacting crop yields by linking data obtained from sensor networks to optimize farming practices.

The IoT platform enables real-time monitoring of soil moisture and ambient temperature, thus ensuring that the crop maintains an ideal environment for growth and development. The fertilization system is also automatically controlled for the distribution of the fertilizer required in the plantation, thus avoiding waste of resources.

Storing data from the sensors and visualizing it in real-time on the IoT platform helps determine possible failures in the autonomous cultivation system. To deepen and optimize the maintenance of data in small, programmed periods.

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