Design and Development of IoT-Based Smart Garden Implementing Edge Computing

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***Abstract*— The agricultural sector in the Philippines is facing a labor shortage, which has significant implications for employment and food security. Additionally, managing water supply has become a critical challenge in agricultural regions due to droughts and increasing competition from non-agricultural sectors. There is a need for urgent and ambitious action to build resilient agricultural and farming systems. This study aims to design and develop an IoT-based smart garden system implementing edge computing and embedding it into the hydroponics system that reduces human intervention in plant production. The system integrates agricultural sensors and actuators through the Internet of Things and edge computing, enabling near real-time monitoring of various parameters. The user-friendly web-based dashboard acts as a monitoring tool, offering garden keepers an intuitive interface to facilitate efficient management. The system underwent development by Prototyping Methodology, which involves hardware identification, installation, and setup, along with data acquisition, preprocessing, and testing. The system underwent evaluation of its accuracy, functionality, and reliability through user-driven testing. The results showed that the IoT-based smart garden system successfully facilitated the growth of lettuce plants and provided dependable monitoring capabilities. Leveraging IoT and edge computing technologies in the hydroponics system offers a modern approach to agriculture, addressing labor shortages and enhancing productivity in the agricultural sector.**

Keywords—agricultural, Internet of Things (IoT), Smart Garden System, agricultural sensors, actuators, web-based monitoring

I. Background of the Design Project

The labor shortage is the most pressing issue in the agricultural sector in the Philippines. The total number of people working in agriculture decreased during the five-year reference period, and in 2019 the agricultural sector employed roughly 9.70 million people. As a result, the nation's total employment from the agriculture sector fell to 22.9%. Western Visayas continues to have the most significant employment in agriculture at the regional level. However, in 2019 it dropped to 873,000 people. In the majority of regions, there was a decline in agricultural employment. On the other hand, Central Visayas, Northern Mindanao, SOCCSKSARGEN, and BARMM all had increases in the number of people working in the agriculture sector, with 657,000, 776,000, 800,000, and 697,000 workers, respectively. In contrast, the minor count in the NCR persisted in 2019, with 25,000 people (Mapa et al., 2020). Moreover, managing water supply is a problem the agricultural sector faces. In recent years, agricultural regions have experienced severe and escalating water restrictions. Significant droughts in Chile and the US have reduced surface and groundwater supplies while affecting agricultural production. In addition to these adjustments, the growing urban population density and the water requirements of the energy and industrial sectors will put farmers in many places at greater risk of competition from non-agricultural users. Additionally, the expansion of polluting industries, salination brought on by rising sea levels, and the aforementioned changes in the water supply are all likely to cause water quality to worsen in many locations. The productivity of rain-fed and irrigated crops and livestock operations, particularly in some nations and regions, are projected to be seriously hampered by these water difficulties, which are expected to impact agriculture significantly. The agricultural sector depends heavily on water. These modifications may significantly affect markets, commerce, and overall food security. Without additional action, Northeast China, Northwest India, and the Southwest of the United States are expected to be among the regions most severely impacted, with consequences for both the local economy and the entire world, according to an Organisation for Economic Co-operation and Development (OECD) assessment of future water risk hotspots (Water and Agriculture - OECD, n.d.).

Despite the decline in the labor shortage, the agricultural sector still provides a living for over 2.5 billion people worldwide. Given the agricultural sector's inherent interactions with the environment, direct reliance on natural resources for production, and the importance of national-socio economic development, urgent and ambitious action to build more resilient agricultural systems is considered necessary. The global population is rapidly increasing, creating a need for safe and secure food to feed this growing population. As a result, traditional farming methods are inadequate to meet this demand (Abd El-Kader & El-Basioni, 2020). In the Philippines, the agriculture sector started as the backbone of the economy before the emergence of the service and industry sector and is now underdeveloped and the least desired by potential Filipino employees compared to the service sector, which is currently the dominant economic sector (2018 Census of Philippine Business and Industry: Economy-Wide | Philippine Statistics Authority, n.d.). Exploring technologies in the agricultural sector, like the Internet of Things (IoT), will promote modernizing agriculture and elevate the sector's economic potential (Kar, n.d.). Internet of Things (IoT) refers to physical things with sensors, computing power, software, and other technologies that can link to other systems and devices via the Internet or other communication networks and exchange data [No Reference]. With the rapid expansion of the Internet of Everything (IoE), more smart devices are becoming online and producing significant amounts of data. This has led to issues with traditional cloud computing models like bandwidth strain, sluggish response times, inadequate security, and poor privacy. Edge computing solutions have emerged since traditional cloud computing can no longer serve today's intelligent society's diversified data processing needs. It is a fresh paradigm for doing calculations at the network's edge. It stresses being closer to the user and the data source than cloud computing. It is portable for local, small-scale data processing and storage at the network's edge. One way to connect physical devices with sensors to other systems is by using a microcontroller such as an Arduino microcontroller. The open-source electronics platform Arduino is built on simple hardware and software. Boards like Arduino can accept inputs like light from a sensor, a touch on a button, or a tweet and translates them into outputs like turning on an LED, starting a motor, or posting something online. Arduino in IoT applications can collect data from a sensor and send the data back to the system or receive data to control actuators. Such technology will benefit the agricultural sector and help mitigate existing problems for years (Cao et al., 2020).

The proponents chose this study to help the agricultural sector combat existing issues/problems. The proponents also believed the study would help farmers adapt to new technology and help manage their farms with a modern approach to producing plant products. The proponents tackled several research problems: How would farmers adapt to the system? How could the system aid farm labor shortage? How would the system manage the water supply? How would the system produce plant products with fewer human interventions? These questions were the reason why the study needed to be studied. This kind of study already existed; however, the proponents tried to innovate and design an almost independent system that farmers could simply adapt, manage, and learn.

II. Statement of Objectives

The study aimed to design and develop an IoT-Based Smart Garden System that raised economical and practical ways of aiding in the production of plants with less human intervention. Specifically, the study aimed to:

- design and develop a multi-sensor system integrated with agricultural sensors and actuators via the internet of things and edge computing;
- develop a user-friendly web-based dashboard to serve as the monitoring tool for the garden keepers;
- Use user-driven testing to evaluate the developed system's accuracy, functionality, and reliability.

III. Conceptual Framework

In figure 1, the carbon dioxide sensor, water level sensor, light sensor, soil moisture sensor, temperature sensor, and water level sensor served as the input sensors of the system connected to the microcontroller/ESP32. The ESP32 acted as a server and a client to send data to the host machine and receive data from the host machine. Using the WiFi/router, the ESP32 server, host machine, database, and web application could exchange data with one another. [1] When the host machine successfully receives the data from the ESP32 server, it inserts it into the database, and the web application can access and display it in near real-time. [2] When the host machine received the data from the database from the web application, it passed it to the ESP32 server and could now collect the data to control the actuators. AC fan, exhaust fan, grow light, submersible pump, and another two water pumps are the actuators/outputs of the system. The actuators are either automated or controlled via the web application. Therefore, the web application or the web-based monitoring system served as both the input and output of the system.

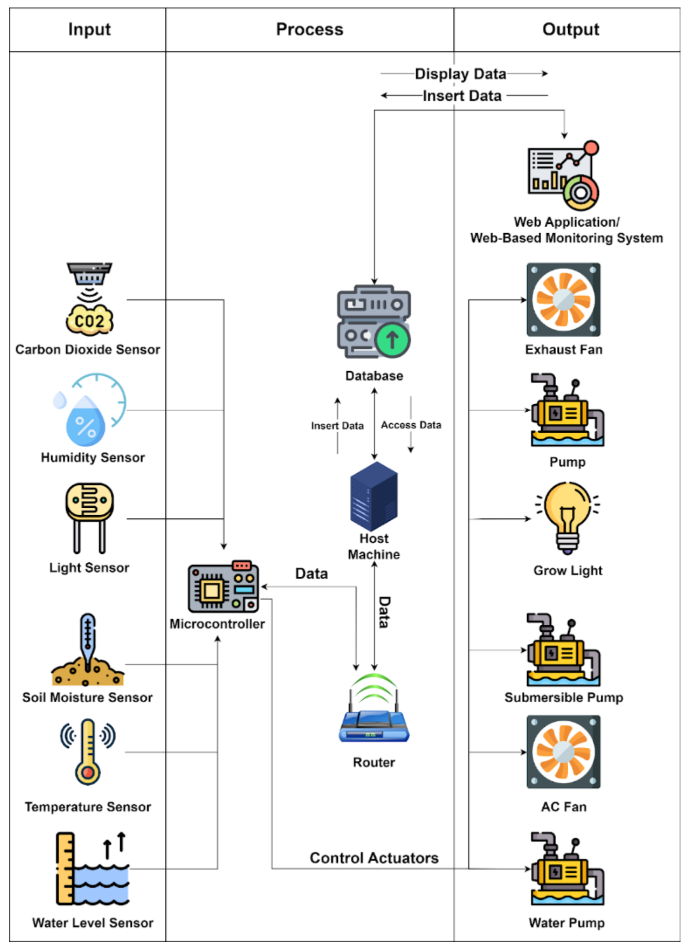

Fig. 1. Conceptual Framework.

IV. Scope and Delimitation

The research is focused on developing and designing a system for the benefit of the agricultural sector, specifically for farmers in Miguela's Farm producing various lettuce. It does not mean the proponent's system will not be suitable for other farmers producing a different product. It will still be suitable, but with modifications, as different plants have distinct characteristics. In short, the system will be designed and developed that is fit for producing lettuce, specifically the

Batavia Lettuce (Scientific Name: Lactuca sativa var. longifolia). Miguela's Farm provided the proponents with a greenhouse there; the proponents implemented the system in a span of 4 months. The system's functions are the following:

- the system detects, automates, and controls the carbon dioxide near the surrounding area of the lettuce plants. If the carbon dioxide goes beyond the given standard value, the system will filter the carbon dioxide;
- the system detects, automates, and controls the soil moisture of the lettuce plant if the plant's soil moisture is below the required amount. The system will moisten the soil with water from the water tank;
- the system detects the water level in the water tank and automate and control the water supply use; If the water in the tank is below the average level, the system will replenish the tank with water until it is filled;
- the system detects, automates, and controls the plants surrounding temperature; if the climate is above the minimum temperature for the lettuce plants to survive, the system will adjust the temperature of the area where the plant is located;
- the system detects and mimics sunlight. Sometimes sunlight is unavailable, and sunlight plays a vital role in plants' survival. If the system detects there is not enough sunlight, the system will provide the lettuce plants with artificial sunlight;
- the system detects, automates, and controls the humidity in the surrounding area of the lettuce plant; if the air has insufficient water vapor, the system will mist water in the vicinity;
- the system senses the air's carbon dioxide content;
- data or relevant data coming from the sensors are collected and stored in the database every 35 seconds;
- on top of this, the system has a web-based monitoring system that monitors the sensor's data in near real-time accessed in the database and can also send data to the server of the microcontroller to control the actuators like grow lights and motors.

Furthermore, the limits of the system are the following:

- it cannot predict or detect weather; the user cannot modify the system's front-end and back-end;
- it cannot protect the harvest from harsh calamities; it cannot protect the harvest from insects/pests;
- the hardware involved in this design project is budget-friendly due to the budget constraints of the proponents.
- the system is not fully automated and still need human intervention;
- the system only implemented edge computing without cloud computing;
- lastly, the users are not able to add plant sections, new sensors, or modify the original layout of the system.

V. DESIGN PROJECT METHODOLOGY

The proponents will decide on prototyping as the development methodology of this design project. The prototyping methodology includes developing, continuously testing, and reworking a system to ensure that the design is acceptable and compatible with development. This methodology allows engaged participation among the potential end user and the proponents of the model. Also, prototyping permits an increased development speed in improving the potential risks and issues associated with the system and its service to its end user. Figure 3 displays a graphical representation of the process used for the system by the proponent. The methodology will begin with hardware identification, where proponents specify hardware components such as microcontrollers, sensors, and actuators needed to provide the lettuce, even in a controlled environment. To be followed by hardware installation showing how the interconnection between the hardware components will transpire. The actuators will be connected to the microcontrollers by the relay module to speed up the link between hardware components and act upon the data based on the readings of the sensors. The sensors that will be in the system are as follows: temperature, soil moisture, humidity, carbon dioxide, light, and water level sensors. The third process in the system is the hardware setup, determining how the proponents will set up the hardware system on miguela's farm. For this, the system will be in the seed germination and growing process in the greenhouse of miguela's farm. The sensors will be used for the seed germination process to initiate the procedure of turning seeds into healthy-grown lettuce plants and for the actual growing process for monitoring and stabilizing the growth progress of lettuce plants. To support the hardware system, the proponents will introduce the use of database software - MySQL Database for handling and storing the data that will come from the hardware system.

On the other hand, WiFi will be present in the system for linking the hardware and the software components of the proponents' system. In data acquisition, only the sensors will be the basis for gathering the appropriate data before it goes through preprocessing. Preprocessing will include preparing the relevant data before raising and displaying it to the Web-based monitoring system that the proponents will develop. This monitoring system will also cater to reports and analytics for further assistance to the end-users on how they can quickly monitor and control the process of growing Lettuce plants. Various testing of the components of the whole system will take place to evaluate and verify whether the system will do what it is supposed to do, prevent errors, and find potential defects in the system. Assuming that the system will be successful, work comes to the stage of implementation and deployment, where end-users will freely use and test the system that the proponents will propose. Lastly, the maintenance of the whole system will materialize. In this stage, the system will successfully deliver its objectives and is compatible with the potential end-users of the model. This stage will also identify that the proponents' system will surely cater to what the end users demand.

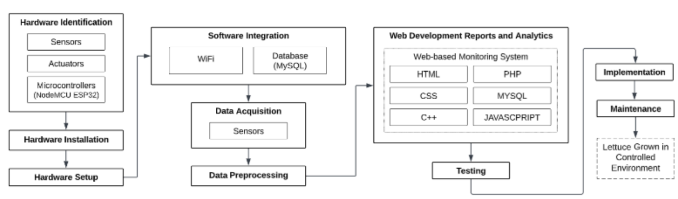

Fig. 2. Overview of the Design Project Methodology.

VI. System Architecture

In figure 3, The first layer of the system consists of sensors and actuators; the following sensors are a carbon dioxide sensor, humidity sensor, light sensor, soil moisture sensor, temperature sensor, and water level sensor, while the following actuators are AC fan, exhaust fan, grow light, submersible pump, and two water pumps. If the data read by the sensors and the written condition in the program complement, the actuators will automate based on the given condition. A relay module connects the microcontroller and actuators to bridge the low-powered microcontroller with the high-powered actuators. The second layer is the edge; several microcontrollers are connected to the sensors and actuators. These microcontrollers will collect and, more importantly, process the raw data into processed data before sending the data to layer four via Router/WiFi. The third layer, WiFi, will enable layers two and four to exchange data. The host machine can gather the processed data in layer four using an HTTP post request. Using PHP script, the processed data will be inserted into the database. There will be two tables, one is for storing processed data, and the other is for storing relevant data. Layer five will house the web application displaying the near real-time processed data and the relevant data accessed from the localhost server MySQL database. The monitoring system will also allow the user to manually activate or deactivate the system's actuators. Different devices can also connect to the web-based monitoring system if the users are connected to the same local area network. The data from the web application will also be stored in the database; using HTTP post request and PHP, the microcontroller can retrieve the data from the database to the host machine to control the actuators. Furthermore, the system will have a second database that will act as a backup in case the first database fails to be accessed, is corrupted, or had data loss.

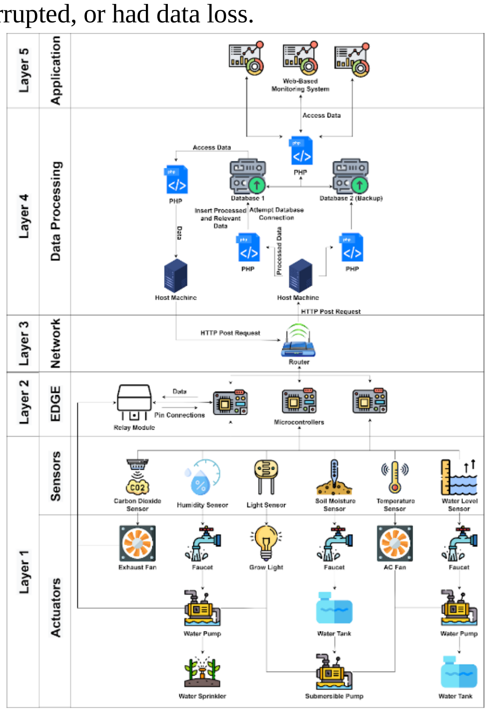

Fig. 3. System Architecture.

VII. Data Gathering Procedures

The proponents will design and develop a prototype to detect any farm environment changes. The sensors will be picked and put on the farm based on the owner's advice and the farm's demands. Following the system's installation, a web-based monitor will be set up to display the sensor data. For this research, the proponents will use different sensors to gather data. The raw data accumulated from the sensors will be processed in the microcontroller. The data will be collected daily, with 35 seconds intervals between collections.

A series of tests are conducted to assess the system's accuracy, functionality, and reliability. The proponents compared the sensor's accuracy with different sensors or testers already available in the market using a percentage error for continuous values and a confusion matrix for discrete values to determine the sensor's accuracy. Furthermore, to assess the system's reliability, the proponents continuously tested the system; using a confusion matrix, the proponents can determine how reliable the system is. Testing the system's functionality, the proponents have surveyed the farmers on Miguela's farm to gather feedback on the system's performance in meeting their specific needs and requirements. This allowed the proponents to evaluate the system's functionality and identify any areas for improvement or additional features that could enhance its usefulness to farmers.

Lastly, Mr. Baeza, the proponent's beneficiary, will test the overall accuracy, functionality, and reliability and validate the system after implementing the system in Miguela's Farm.

VIII. Results and Discussion

The proponents continuously tested the accuracy of the sensors and the system 30 times each; this determines how reliable the system is in growing lettuce. As mentioned in Chapter 3, the proponents used percentage error and confusion matrix to gather how accurate the sensors are and how reliable the system is. All numerical values will then be consolidated into tables located in the appendices. The said numerical values will be compared to the standard (ideal) values from table 2 in chapter 2.

TABLE I. Average Accuracy of the 6 Sensors of the System

	Average Sensor Accuracy	Average Third-Party Sensor Accuracy	Average Percentage Error
Carbon Dioxide	452.13 PPM	489.63 PPM	9.56%
Humidity	64.57%	49.13%	31.44%
Temperature	31.93°C	33.5 °C	5.02%
Light Sensor	1522.23 Lux	1597.67 Lux	8.59%
Soil Moisture	53.8%	47.74 %	12.84%

The carbon dioxide sensor shows varying values and an average of 452.13 PPM from the system but never exceeds 500 PPM. The third-party sensor shares a similar value with the occasional outliers and an average value of 489.63 PPM but does not exceed 600 PPM, below the standard values of 800 PPM to 1200 PPM required for lettuce growth. The percentage error ranges from a minimum of 0.42% to a maximum of 24.82% and averages 9.56%. Testing of the sensor was accomplished by allowing the sensor to measure the carbon dioxide emissions from brunt newspaper and would activate the corresponding actuator to disperse the carbon dioxide gas. According to an article written by Florida Atlantic University (2023), sources of carbon dioxide appear naturally in the atmosphere due to the decay of organisms, volcano eruptions, forest fires, etc. When hydrocarbon fuel (Wood, oil, fossil fuel) is burned, carbon dioxide and water vapors is emitted when the carbon from the fuel interacts with the surrounding oxygen. The system provided a low variability of humidity values within 62% to 69% and averaged at 64.57%, while the third-party sensor provided similar groupings ranging from 46% to 53% and 49.13%. The values provide the proponents with percentage values ranging from 26% to a maximum of 38% and averaging 31.44%. The values show that the humidity is consistent throughout testing and falls within the standard range of 40% to 80%. The system presented low variability of temperature values from the temperature sensor. From a minimum of 30℃ to a maximum of 34℃ and an average of 31.93℃, while the third-party sensor shows similar readings ranging from 31℃ to 35℃ and an average of 33.5℃. All are within the standard growing range of 18C to 26C for lettuce to grow. The table shows that the system can provide the user with temperature readings with a small margin of error, only reaching an error percentage of 11.76% and an average percentage error of 5.02%. The system's light sensor shows a high variability of Lux values. The third-party sensor also shares the same variability of values and sometimes shows a percentage error of 0% to a maximum of 35%. The average Lux value of the system, 1522.23 Lux, and third party sensor, 1597.67 Lux, are on the higher end of the spectrum while the percentage error averages at a reasonable 8.59%. Both values go beyond the standard range of 282.60 Lux to 421.74 Lux, which is the ideal range to supply light to the lettuce. The soil moisture presents consistent and averages at 53.8% moisture value, while the third-party sensor says otherwise. The third-party sensor shows a range of values from 45.13% to 49.59% and averaging at 47.74%, which provided low variability of distribution at a lower range compared to the range of the soil moisture sensor of the system, with both being on the lower end of the standard range of 50% to 80%. The percentage error ranges from 8.08% to 19.65% and averages 12.84%.

In Fig. 4, the testing of the water level sensor provided the proponents with 100% confidence in the accuracy of the water level sensor when activated by external stimuli.

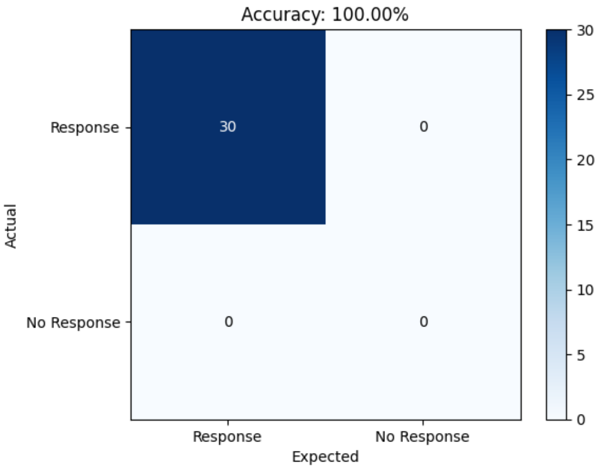

Fig. 4. Accuracy of the Water Level Sensor.

In Fig. 5, the sensor-to-actuator response achieved an accuracy value of 100% during testing. It provided the user with a responsive actuator control to mitigate the undesired levels of carbon dioxide gas surrounding the lettuce.

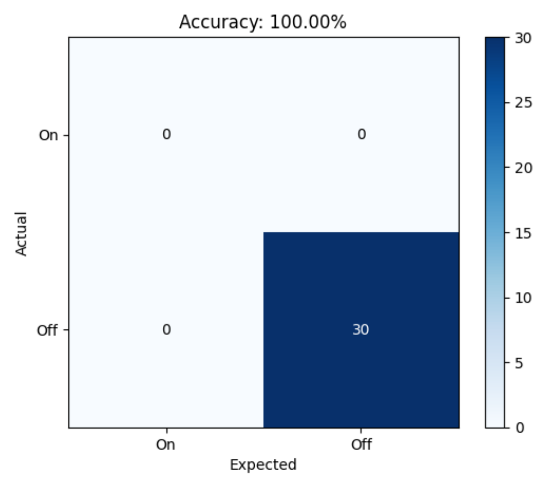

Fig. 5. Confusion Matrix for the Actuator of the Carbon Dioxide Sensor.

In Fig. 6, the response accuracy achieved during continuous testing by the actuator of the humidity sensor is 100% and proves the accuracy of the responsive actuator control. This will provide users with control of water management.

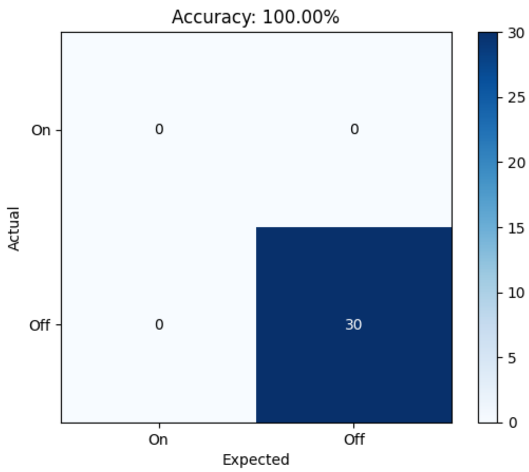

Fig. 6. Confusion Matrix for the Actuator of the Humidity Sensor.

In Fig. 7, the system also achieved 100% in the response testing of the actuators of the light sensors and ensures that the artificial light source will be active when sunlight is not abundant or otherwise.

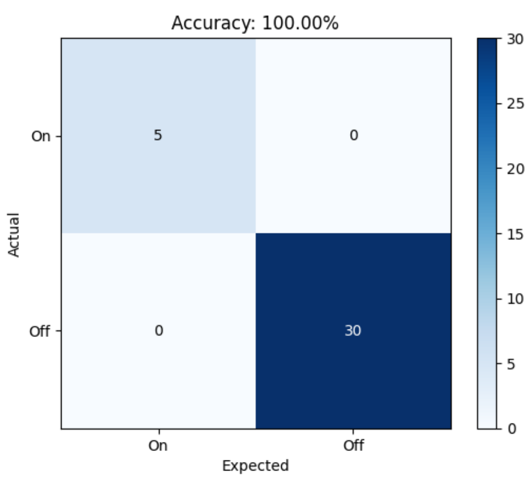

Fig. 7. Confusion Matrix for the Actuator of the Light Sensor.

In Fig. 8, the system acquired 100% in the accuracy of the actuator of the soil moisture sensor as the system provides the soil with a good water source at appropriate intervals to avoid drying out the lettuce soil. The system will ensure that the user uses efficient water management to minimize water waste.

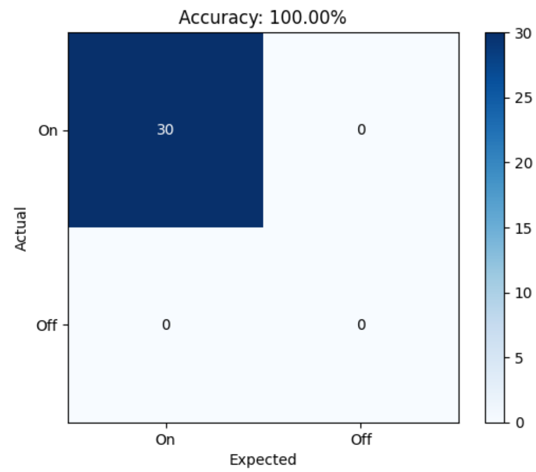

Fig. 8. Confusion Matrix for the Actuator of the Soil Moisture.

In Fig. 9, the actuator of the temperature sensor responds to the stimuli collected by the temperature sensor 100% of the time during the testing phase; this will allow users to fully manipulate the temperature surrounding the lettuce and efficiently manage electrical resources.

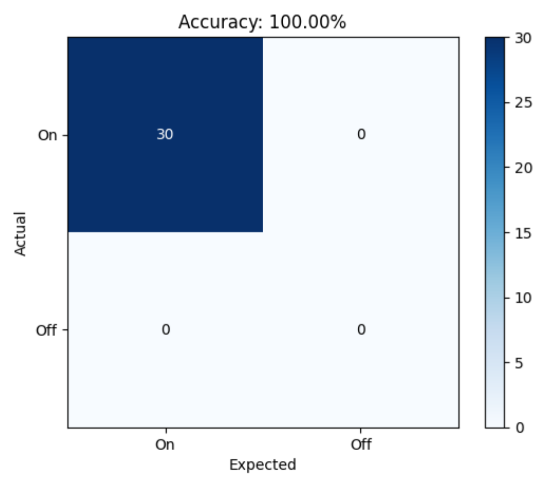

Fig. 9. Confusion Matrix for the Actuator of the Temperature Sensor.

In Fig. 10, the actuator of the water level sensor responded accurately 100% of the time during testing. This goes hand-in-hand with activating the soil moisture sensor's actuator, reducing water waste, and providing better water management.

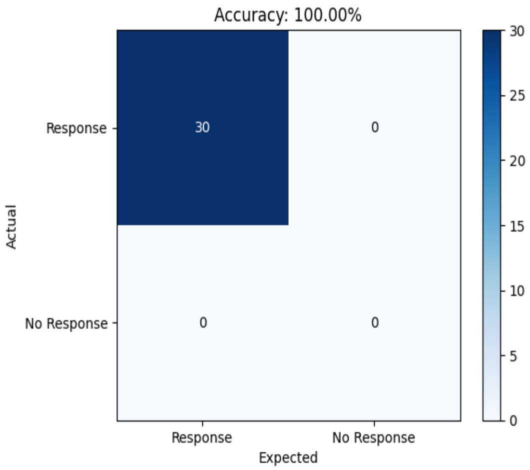

Fig. 10. Confusion Matrix for the Actuator of the Water Level Sensor.

In Fig. 11, the bypass actuators system proves reliable in controlling the actuators and demonstrates exceptional performance with a remarkable 100% accuracy achieved during testing. This outstanding accuracy showcases the system's effectiveness and reinforces its reliability in accurately manipulating the actuators as intended. The flawless precision achieved by the bypass actuators system further solidifies its suitability for critical applications where precise control and consistent performance are of utmost importance.

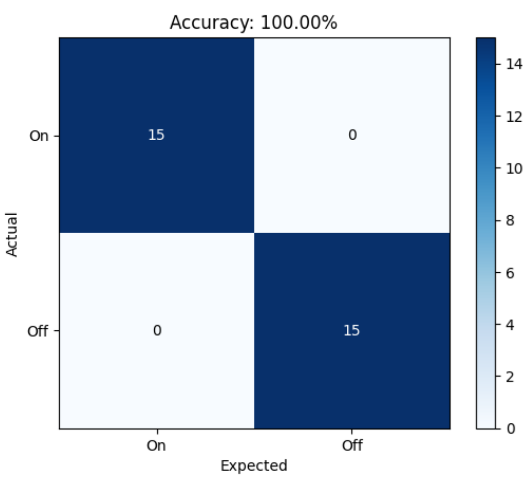

Fig. 11. Reliability of the Bypass System.

IX. Conclusion

Overall, the findings indicate that the system's sensors provide accurate readings within acceptable ranges for lettuce growth. The actuators exhibit precise and reliable control, ensuring efficient management of environmental factors for lettuce cultivation.

The IoT-based smart garden system implementing edge computing was successfully designed and developed, integrating multiple agricultural sensors and actuators through the Internet of Things and edge computing. This system enables near real-time monitoring of parameters such as temperature, humidity, soil moisture, light, carbon dioxide, and water level. Additionally, A user-friendly web-based dashboard was successfully developed to serve as a monitoring tool for the garden keepers. This dashboard provides an intuitive interface for monitoring the data collected by the sensors. Furthermore, the proponents have successfully tested the system's accuracy, functionality, and reliability through user-driven testing and found out that the system is dependable in growing lettuce plants.

X. Recommendation

Due to budget constraints, the system has only used the typical fan and failed to adjust the surrounding temperature of the environment. However, removing the budget constraint, the proponents suggest replacing the fan with an air conditioner to better impact the temperature surrounding the lettuce plants. Moreover, the proponents also recommend that the system is adequate in indoor planting, especially the temperature, where the environment is controlled. The system is not perfect and still needs to be improved to enhance further the system's performance; ongoing research and development should be conducted to identify areas for improvement and optimize the system's capabilities.

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