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Investigating an Enhanced Approach for Greenhouse Climate Control: Optimising Cooling and Heating Systems

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Abstract— **This study aimed to enhance greenhouse climate regulation by optimizing the efficiency of existing cooling and heating systems while considering external temperature and humidity conditions. We introduced an automated system capable of regulating the internal greenhouse environment, which underwent testing across 30 days in September 2021, with temperatures ranging from 26°C to 31°C and humidity from 65% to 70%. The system consistently monitored and adjusted the microclimate, with sensors capturing temperature and humidity data at 30-second intervals, amassing over 83,000 data entries for enhanced control accuracy. The automated regulation effectively maintained desired humidity, significantly reducing nighttime levels by 80% while carefully increasing daytime humidity to counteract external heat. Temperature control was largely successful, sustaining daytime levels around 32°C, but faced challenges in maintaining the target of 26°C during cooler nights. Energy consumption was optimized, with the automation leading to a significant 4-33% energy saving for cooling and an 8% saving in heating compared to traditional methods. Additionally, the system was accessible via a web interface, allowing for real-time climate tracking and prompt anomaly identification. In conclusion, the developed greenhouse automation system exhibited efficiency in equipment usage and improved temperature and humidity control. Further enhancements are required for lamp-based heating. This research contributes to the efficiency and reliability of greenhouse automation systems, mitigating risks associated with external environmental factors and enhancing stability, productivity, and disease and pest prevention.**

Keywords— **Greenhouse climate control; tropical country; automation system; energy efficiency.**

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I. INTRODUCTION

Climate change is an ongoing natural process that occurs over long periods. Human activities in various sectors such as industry, fossil fuel utilization, waste, and others primarily cause it. These activities result in the greenhouse effect, leading to a global increase in surface temperatures [1], [2]. The impacts of global climate change include altered rainfall patterns, increased extreme weather events, and rising air and sea surface temperatures[2], [3]. The agricultural sector, particularly in Indonesia, is highly vulnerable to these climate changes. Food crops are seasonal and sensitive to water excesses and deficiencies. Consequently, farmers must adapt by implementing new technologies and strategies to cope with serious issues that threaten agricultural production. In addition to the factors mentioned earlier, decreased productivity is also attributed to soil fertility degradation resulting from pesticide use and conventional fertilization practices, environmental pollution, and land conversion [4], [5].

Technological adaptation is expected to be critical to the success of the agricultural sector under the growing threat of climate change impacts. In Indonesia, a tropical country [6], farmers have already adopted greenhouse systems for seedling production and crop cultivation. Although the scale of greenhouse utilization is smaller than conventional farming methods, this system has shown promising results for farmers.

Several reasons make greenhouses an appealing choice. Greenhouses are enclosed spaces that can create a different climate from the external conditions, making it easier for farmers to control crucial parameters such as temperature, humidity, irrigation systems, and fertilizer application tailored to the specific needs of plants[1], [7]–[11].

The concept of a greenhouse aims to minimize or even eliminate the adverse effects of climate on plants inside. In addition to controlling the environment, greenhouses are also utilized to protect plants from pest attacks. Greenhouse construction in Indonesia, particularly in urban areas, is rapidly expanding. Factors such as weather conditions, limited availability of agricultural land, and the demand for organic food contribute to this growth.

Greenhouses are extensively used in plant management, including seedling production, cultivation, and crop yield. However, the control measures within greenhouses are still largely manual, with farmers manually performing tasks such as watering in the morning and evening without considering the required soil moisture, inadequate fertilizer application according to plant nutrient needs, and greenhouse temperature regulation through window openings, which can allow pests to enter the greenhouse and hinder optimal plant growth. Additionally, time management and the lack of tools to assist farmers pose challenges in manual greenhouse management, thus hindering the optimal quantity and quality of crop production [12], [13], [14] due to technical and non-technical errors, such as inaccurate temperature monitoring, humidity measurement, and ideal watering periods. This study explores a new approach to climate control within greenhouses by optimizing the operation time of the available cooling and heating systems, considering the external temperature and humidity conditions. This approach aims to enhance energy efficiency within the greenhouse.

II. MATERIALS AND METHOD

A. *Internet of Things (IoT) in the Agriculture Industry*

The Internet of Things (IoT) is a massively developing platform with extensive applications to support various sectors in everyday life. One sector that significantly benefits from this technology is the agricultural industry[15]–[18]. IoT technology can reach vast agrarian areas, collecting and transmitting environmental data efficiently, thus providing convenience for farmers to monitor and control plants effectively and sustainably.

IoT has revolutionized perceptions and farming methods in many countries. From initial stages to marketing, agricultural production activities have undergone significant changes, making farming more precise, efficient, and profitable for farmers [12]. The implementation of IoT technology in the agricultural sector is generally used for environmental monitoring by connecting necessary sensors and controlling essential parameters for farmers. Embedded systems are often the preferred choice for building IoT-based communication due to their low cost, low power consumption, and sufficient capabilities.

Research discussing the development of the agricultural industry with IoT implementation indicates that IoT architecture consists of four layers: application, service, communication, and physical [19]. The application layer typically involves building an application used for control, prediction, logistics delivery, and monitoring of agricultural activities. The applications can vary from web-based[12] to desktop and mobile[10]. The service layer comprises several services to assist and maintain data transformation from the communication layer. The functions of this service layer include communication between nodes, gateways, and servers, data storage in databases, analysis requirements, data visualization, and security.

The next layer is the communication layer, which transfers data from the physical layer to the service layer. The communication layer can be wired or wireless, depending on the needs and environmental conditions of the developed system. Typically, the communication layer includes gateway devices responsible for collecting data from sensor nodes connected via Bluetooth, LoRa, SigFox, and other media. The physical layer consists of microcontroller devices connected to various sensors that read the conditions of plants, soil, air, and others. Subsequently, the data is sent to the gateway and the layers above. These microcontrollers are also connected to actuators that control the environment or plants according to instructions from the layers above[20]–[22].

B. *Smart Greenhouse*

Smart greenhouses are developed for monitoring and control purposes, to provide precise feedback control, and to predict future climate changes. The decision-making process for particular responses in smart greenhouses utilizing fuzzy logic methods has yielded satisfactory results. Additionally, machine learning methods anticipate adverse plant conditions caused by extreme external weather conditions, such as freezing temperatures. Greenhouses can create a climate different from the conditions outside [16]. In its development, greenhouses are widely used in areas with unproductive agricultural land due to extreme weather conditions that can damage crops. Proper greenhouse control techniques are highly effective in preventing the adverse effects of unfavorable climates [23], [24].

In Indonesia, research on smart greenhouses has been growing rapidly. However, implementing smart greenhouses for production has yet to be fully optimized. Many farmers utilize smart greenhouses for seedlings, research, and small-scale experiments. Apart from the high costs of greenhouse construction, operational expenses, and infrastructure maintenance remain major factors that hinder the development of this system for large-scale production.

In principle, a smart greenhouse represents a transformation of manual climate control inside the greenhouse into an automated and controlled approach. Smart greenhouses typically regulate two main parameters: humidity and air temperature. However, as it progresses, other sensors are also used to control pH levels, nutrient delivery, and soil moisture to achieve ideal plant conditions[25]–[27].

External factors such as outside temperature and solar radiation significantly impact the distribution of solar irradiation within the greenhouse [28]. A previous study was conducted in central Tunisia during summer climate conditions. The study found that as solar radiation penetrates the greenhouse, the diffuse sky solar radiation gradually increases and reaches its maximum value at the roof of the structure.

The role of IoT platforms in the development process of smart greenhouses is significant. In addition to processing data for decision-making to maintain climate stability inside the greenhouse, the functionality of IoT is closely tied to providing convenience for users to monitor in real-time and adjust parameter values. Previous studies have shown the successful development of smart greenhouses utilizing IoT for tomato plants [12].

They implemented IoT to maintain temperature and humidity in the greenhouse, utilizing mist cooling. Humidity and temperature data within the greenhouse could be accessed via the internet network using a smartphone application, updating every 20 minutes. The system was built using an SHT11 sensor and a GUVA-S12D sensor for light intensity. The system did not employ a heater to raise the temperature if the conditions inside the greenhouse were too cold, which could occur with high solar radiation. The dimensions of the greenhouse used in the study were not specified. However, the system could regulate the temperature between 20-28°C and humidity between 80-90% according to the needs of tomato plants.

Developing larger or multi-location integrated smart greenhouses will require more complex communication systems. A wireless sensor network (WSN) consisting of several sensor nodes and a gateway was implemented to reach remote locations [20]. This study connected each sensor node to STM32 and serially transmitted it to NB-IoT. NB-IoT wirelessly transmitted data to the database using the COAP protocol through the GPRS network. Subsequently, the data was presented to users through web and mobile interfaces. Eight nodes were connected, with each NB-IoT device connected to four nodes, relaying the data to the cloud.

C. Climate Control in Tropical Greenhouse

In practice, several methods exist to control the greenhouse climate, like natural ventilation[29], mechanical ventilation [24], cooling [22], and heating systems. Ventilation techniques in greenhouses in tropical regions increase the air temperature when the outside air is cooler than the inside. This ventilation technique can also control air humidity, benefiting plant growth. Natural ventilation is applied in greenhouses in tropical areas to circulate air from outside to inside the greenhouse or vice versa [6]. This airflow occurs due to the difference in pressure and temperature inside and outside the greenhouse. However, greenhouses in tropical areas that implement natural ventilation can generally ensure that the inside air temperature is always higher than outside. This condition becomes a major problem during the dry season when the cooling system operates at maximum capacity.

Several studies have been conducted previously to develop environmental control models in greenhouses, where the control algorithm for greenhouses has different dynamics and situations. In general, automation in greenhouses in tropical areas involves techniques to control the climate automatically, hoping to increase energy efficiency and maximize plant growth benefits. A good understanding of the control parameters and how they interact with other parameters within the greenhouse needs to be studied to design an optimal control algorithm.

The feedforward approach is a method where deviations are measured before the disturbance affects the system [11]. For example, if the system detects a change in ventilation status, it will automatically adjust the temperature control before a significant deviation from the setpoint occurs. Based on a physical model, they design a feedforward controller for greenhouse climate control. If feedback correction is used with feedforward control, a high level of precision can be achieved.

In the simple feedback control approach [11], decisions are based on the difference between actual measurements and desired parameters. If there is a deviation, the controller will respond to return to normal conditions. However, this system operates slowly and oscillates above and below the input. This method is useful in situations that demand a low level of precision.

The self-tuning method uses parameters within the greenhouse to adapt and minimize errors in the controlled system. This method is usually used with artificial intelligence, such as fuzzy logic [30], [31]. This adaptive controller has a one-step-ahead characteristic. If the parameters of the controlled system are uncertain or variable, the control laws in the adaptive controller allow control parameters to be continuously adjusted to changing conditions. However, the greenhouse control process in tropical regions needs to follow a more complex configuration. For example, the influence on temperature changes when controlling humidity or vice versa.

Greenhouse innovations are particularly apt for emerging economies despite the substantial upfront costs of greenhouse infrastructure. Critics highlight the issue of significant energy usage within these structures and the considerable expenditure required for their upkeep. Additionally, the approaches above have yet to be trialed in the climatic conditions' characteristic of tropical regions.

In this research, a control system, as shown in Fig. 6, was developed consisting of several sensors, both inside and outside, which monitor all the important environmental variables that affect plant growth, as shown in Fig.3. This sensor data is then fed to the controller. The controlled environmental parameters will be changed through predetermined commands that have been programmed and related actuators such as fans, coolers, heating systems, and sprayers. This must be done in an integrated manner, where cooling and ventilation must be carefully synchronized to control temperature and humidity without wasting valuable energy from unnecessary ventilation. However, using two or more sets of independent sensors is also expected to guarantee the accuracy of system monitoring and control.

This research was conducted in a greenhouse in the Agribusiness Study Program at Banyuwangi State Polytechnic, as shown in Fig.1. The greenhouse is a research facility in agriculture where various types of plants are studied. Therefore, different temperature and humidity conditions are often required to support the resilience of plants inside the greenhouse. The equipment available in the greenhouse includes cooling and heating systems, as shown in Table 1. Two standing Air Conditioner units are used for cooling purposes, while eight lamps are provided as heaters and positioned at the top of the greenhouse.

So far, the greenhouse, which has a width of 6m and a length of 24m, has been manually controlled and monitored for temperature and humidity. Staff members must constantly come and go to maintain the desired temperature and humidity levels. Apart from requiring human resources, this method could be more effective in ensuring that the greenhouse consistently maintains suitable plant conditions. Therefore, this study focuses on transforming the greenhouse from manual control to an automated system without altering the existing equipment.

Fig. 1 Greenhouse Agribusiness Study Program

This research was conducted for three months, from July to September 2021. The first step of this study involved observing the temperature and humidity conditions inside and outside the greenhouse [1], [23], [28] under three different weather conditions: rainy, cloudy, and sunny.

TABLE I
GREENHOUSE APPARATUS

No.	Greenhouse apparatus	Specification	Qty (Unit)
1	Air Conditioner	- Voltage: 220 VAC - Wattage: 7,3KW - Capacity: 24,900 Btu/h	2
2	Blower Fan	- Fan Diameter:900mm - Wattage: 750Watt - Voltage: 220VAC - Flowrate:25000m^3/h	4
3	Lamp	- Voltage: 220 VAC - Wattage: 15 Watt	8
4	Sprinkle Pump	- Voltage: 12VDC - Max pressure:100psi - Number of mist points: 10	4

Based on the initial observations, the temperature conditions in the greenhouse location showed a significant increase from morning to afternoon, with a maximum temperature ranging from 32°C to 34°C. The air temperature remained relatively stable from night to early morning, ranging between 24°C and 26°C. The temperature changes inside the greenhouse followed a linear pattern, but during the morning to afternoon, the temperature inside the greenhouse could reach as high as 35°C to 37°C, while during the night to morning, the temperature inside the greenhouse remained relatively warm compared to the outside temperature, ranging between 29°C and 31°C.

Relative humidity (RH) values exhibited an inverse relationship with temperature. As the temperature increased, the air humidity decreased, and vice versa. However, in the conducted observations, the humidity outside the greenhouse fluctuated and was generally lower. It was influenced by factors such as wind and unfavorable weather conditions. Nevertheless, these factors had a relatively small impact on the conditions inside the greenhouse.

In this study, a system was developed to regulate the humidity and temperature levels based on user-defined parameters. The method involved controlling the activation of equipment (Air Conditioner, Blower Fan, Lamps, Sprinkle Pump) inside the greenhouse. Before activating each piece of equipment, the temperature and humidity data inside the greenhouse were compared with those collected outside the greenhouse. Two sets of sensors, LM35 and SHT sensor [17], were used in this study, with one set placed inside the greenhouse and the other set placed outside, as shown in Fig.2.

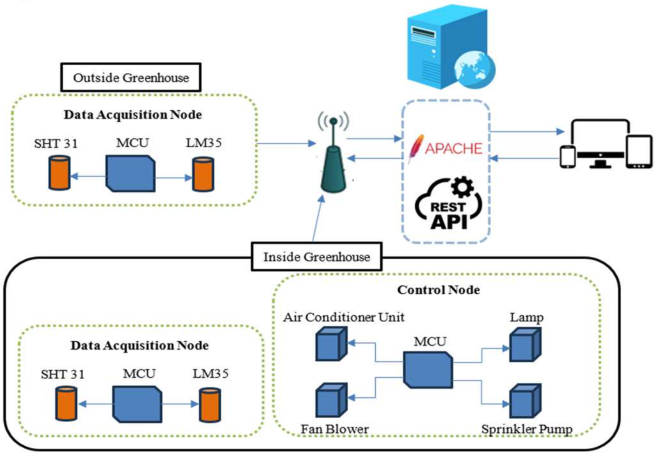

Fig. 2 Structure of IoT-Based Web System

Each piece of equipment was connected to a microcontroller [21], [27] with a relay driver to control the fan blower, sprinkler pump, and lamps. Transistors were added to isolate the microcontroller from the 220-volt AC voltage, and the control system implemented an on/off control. As for the Air Conditioner unit, each was controlled using a 940nm infrared LED to replace the remote control. The Air Conditioner was previously set to the cooling mode with the minimum temperature, so the microcontroller only functioned to turn it on and off.

All microcontrollers were wirelessly connected to an access point and transmitted the data to the server. The web application was built using the MVC framework[32], where communication from the node was routed after the framework received a request from the browser. This system implemented the Rest (Representational State Transfer) architecture and HTTP protocol. The Rest Clients used HTTP Requests to communicate with the server using URLs. The server then responded and sent back the requested HTTP data. The data provided by the Rest server was in JSON format.

III. RESULT AND DISCUSSION

A. Temperature and Humidity Control System

Before collecting temperature and humidity data, the LM35 temperature sensor and SHT31 humidity sensor were calibrated using a mercury thermometer and a calibrated air humidity sensor. Correlation analysis compared whether the proposed sensors could produce accurate values. Linear regression was used to compare the coefficients (R2) and root means square error (RMSE) [33]. The experiment was conducted for one month to obtain sufficient data variation during rainy, cloudy, and sunny weather conditions. The data were saved in (*.csv) format, and Tableau software calculated average values per hour. Thus, the number of data points (n) was 24. The RMSE values were analyzed using the equation provided in Equation 1.

$$RMSE = \sqrt{\frac{1}{n} x \sum_{i=1}^{n} (predict - obs)^2} \qquad (1)$$

Where "predict" represents the calibrated sensor values and "obs" represents the values obtained from the measurement tool.

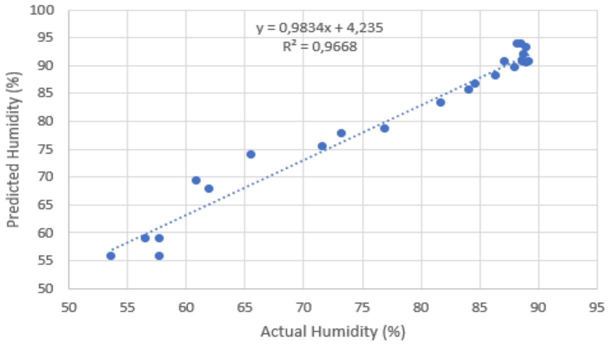

Fig. 3 Humidity Sensor Correlation Analysis

Based on Eq.1, the RMSE value can be calculated to determine the level of sensor calibration with the measurement tool. From the calculations as shown in Fig.3 and Fig. 4, the temperature parameter has an R2 value of 0.861 and an RMSE of 1.92, while the humidity parameter has an R2 value of 0.968 and an RMSE of 3.76. Based on these values, it can be concluded that the sensor can be used for this research.

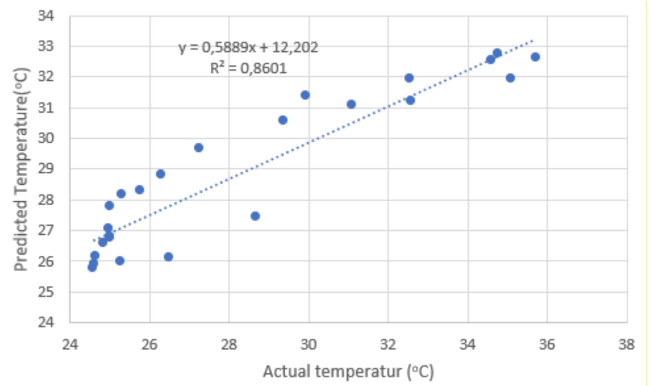

Fig. 4 Temperature Sensor Correlation Analysis

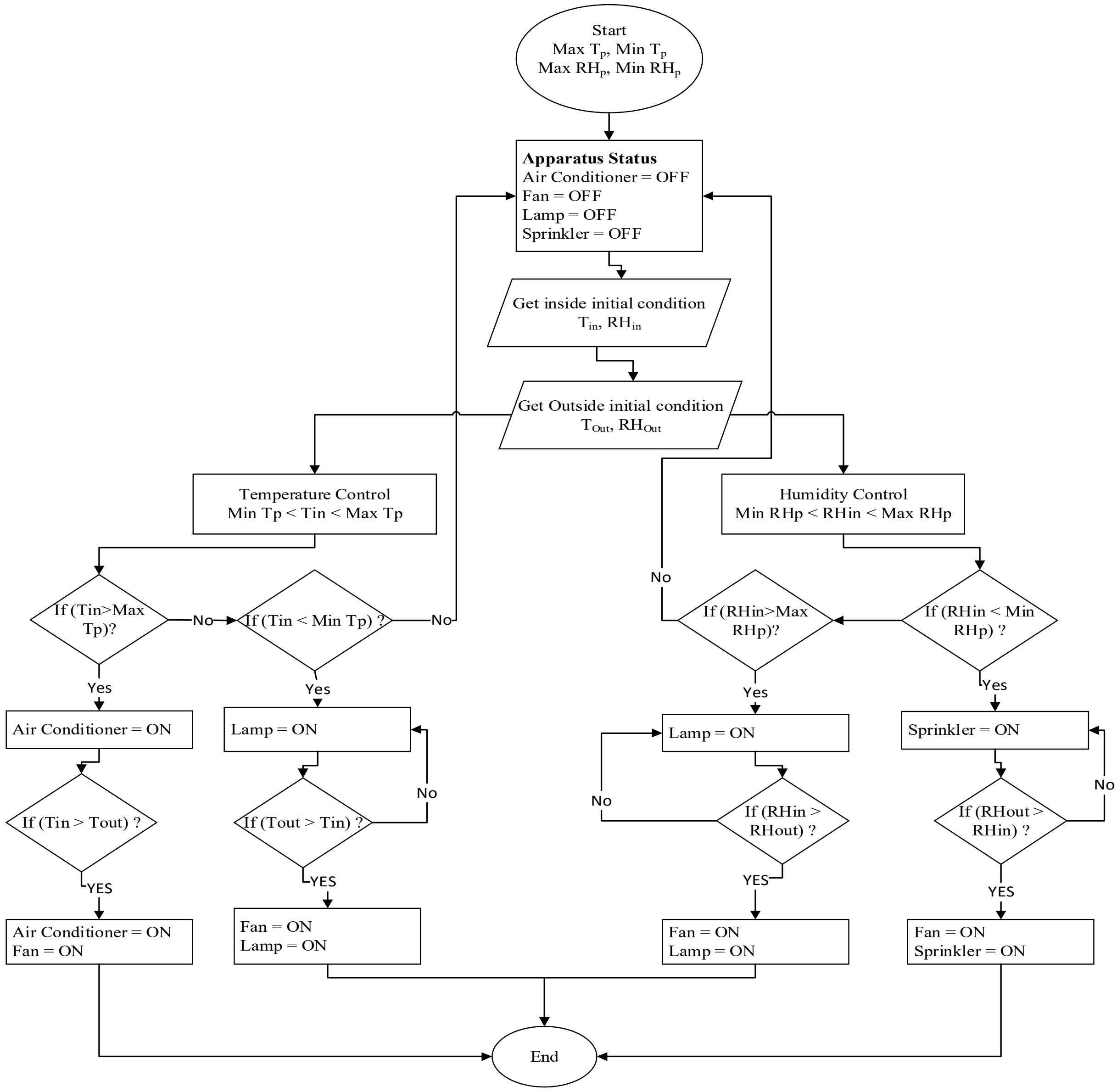

Fig. 5 Flowchart the Logic of the Control Method

The control method used in this study is to minimize the operating time of the available apparatus inside the greenhouse and energy efficiency [13], [29], [34] as shown in Fig. 5. Suppose the temperature inside the greenhouse (T_{in}) exceeds the maximum temperature parameter value (T_P). In that case, the Air Conditioner will be turned on, and the blower will be activated if the temperature outside the greenhouse (T_{Out}) is lower than T_{In}.

However, if the temperature inside the greenhouse is colder than the minimum T_P value, such as during the night, the lamps will be turned on. The blower will also be activated if T_{Out} is greater than T_{In}. A similar principle applies to humidity control. When the air humidity inside the greenhouse (RHIn) is higher than the maximum humidity parameter value (RHP), the lamps will be turned on, and the blower will be activated if the humidity outside (RHOut) is lower than RHIn. Similarly, the sprinkler will be activated when RHIn exceeds the minimum RHP value. The testing of the built system, as described in the previous chapter, was conducted to determine the performance and reliability of the automation system in maintaining the temperature and humidity of the greenhouse within the predefined range. The testing was conducted for 30 days in September 2021. The temperature parameter (T_P) used ranged between 26°C and 31°C, while the humidity parameter (RH_P) used was within the range of 65% - 70%.

Sensor data and equipment status inside the greenhouse were collected every 30 seconds based on the temperature changes occurring inside the greenhouse. In contrast, the temperature outside the greenhouse did not fluctuate significantly within a short period. The sensor's average time interval for detecting temperature and humidity changes was between 10 and 58 seconds. In a single day, a total of 83,292 data points were obtained. With such frequent data updates, it is expected to control the microclimate conditions inside the greenhouse as accurately as possible.

In the initial stage, observations were made on the temperature and humidity data obtained without any control or plants affecting the greenhouse's microclimate values. Then, the data was processed using a spreadsheet application to differentiate it based on weather categories, such as sunny, cloudy, and rainy conditions. Based on the results obtained in Fig. 6, it can be observed that the humidity values inside the greenhouse varied significantly under these three conditions.

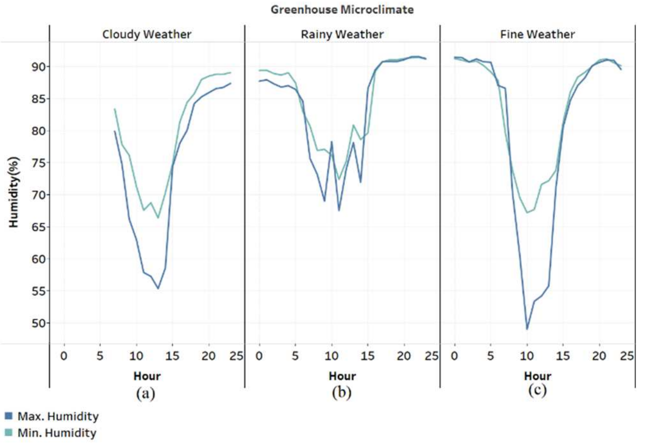

Fig. 6 Minimum and Maximum Humidity in (a). Cloudy weather, (b). Rainy Weather, (c). Fine Weather

During rainy conditions, the relative humidity values inside the greenhouse are relatively high, ranging from a minimum of 55% to a maximum of 80%, compared to other weather conditions. During cloudy weather, the minimum humidity value is almost the same as during sunny weather, around 40%, especially during the daytime. The maximum humidity during cloudy weather differs by up to 10% compared to sunny weather conditions. From the data mentioned, there is a significant difference in humidity values inside the greenhouse between daytime and nighttime, as well as during rainy and non-rainy conditions. These conditions are not favorable for plants, so the greenhouse requires humidity control to ensure optimal growth of the plants inside it.

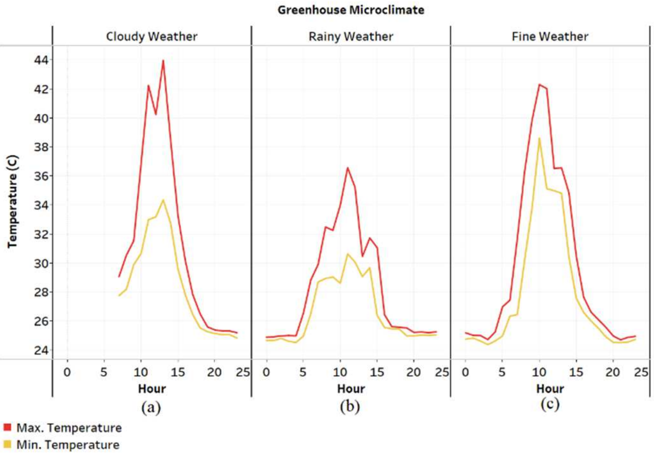

Fig. 7 Minimum and Maximum Temperature in (a). Cloudy weather, (b). Rainy Weather, (c). Fine Weather

The temperature inside the greenhouse also exhibits significant variations during rainy, cloudy, and sunny weather conditions. As seen in Fig. 7, the highest temperature recorded inside the greenhouse was 44°C during cloudy weather and 42°C during sunny weather. Meanwhile, during the rainy season, the maximum temperature reached 36°C. The lowest temperature inside the greenhouse occurred during the rainy season, with a minimum temperature of 29°C during the daytime and 24°C during the nighttime. This temperature range is unfavorable for plants, so temperature control is necessary to achieve the ideal temperature for plant growth. Based on Figures 7 and 8, it can be observed that the external weather conditions have a significant impact on the microclimate inside the greenhouse.

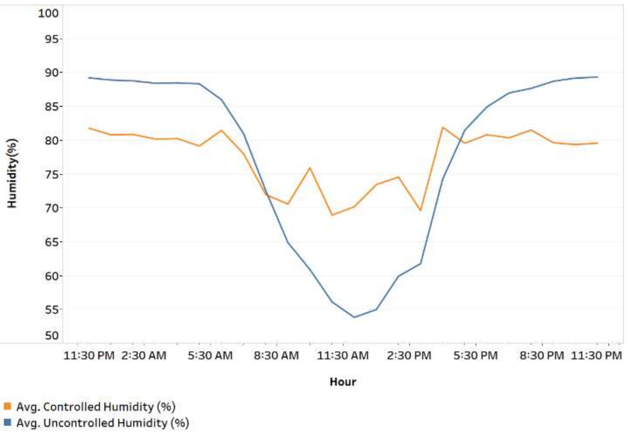

Fig. 8 Average Controlled and Uncontrolled Greenhouse Humidity

Therefore, in the subsequent testing, the control of the microclimate inside the greenhouse was implemented and compared with the outside conditions. The automation system, as outlined in Fig.5, demonstrated its effectiveness, as shown in Fig. 8. The test results indicate that the constructed system can effectively control humidity within the predetermined range. Based on the observations, the humidity outside the greenhouse (RHOut) reached 90% during nighttime. However, the lamps and blowers that introduced fresh air effectively reduced the humidity inside the greenhouse (RHIn) by up to 10%. On the other hand, during the daytime, the sprinkler pump played a significant role in increasing the humidity inside the greenhouse by up to 15% compared to the humidity outside.

Fig. 8 shows that although the system can maintain the humidity within the specified range (RHP) of 65% - 70%, there are fluctuations in the values during the daytime. The data indicates that the sprinkler is highly effective in increasing humidity, but the high temperature from the outside also significantly reduces humidity inside the greenhouse. Fig. 9 shows the comparison between the controlled temperature inside the greenhouse and the temperature outside. The cooling system inside the greenhouse functions well, especially during the daytime, maintaining the temperature within the range of 32°C. However, the heating system uses eight lamps during nighttime and struggles to reach a temperature of 26°C. Fig. 9 shows that the temperature outside (T_{Out}) is below the parameter temperature (T_P), resulting in the fan blower, which should help maintain the temperature, not being activated.

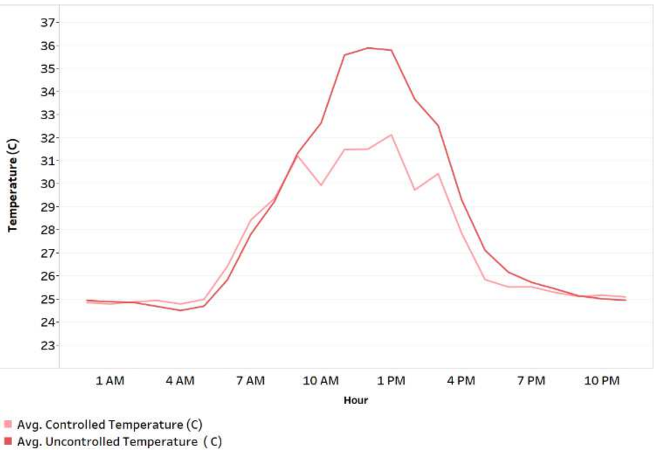

Fig. 9 Average Controlled and Uncontrolled Greenhouse Temperature

Temperature and humidity data, as well as the status of equipment, can be accessed in real-time through a website page to assist users in monitoring anomalies or detecting equipment that is not functioning. Each activation of the equipment is recorded and stored in the database. The activation times are then compared with the previous manual activation method. In the previous method, the greenhouse equipment was manually turned on, with the AC and blower running for eleven hours during the daytime and the lamps turned on during the nighttime. On the other hand, the sprinkler was activated as needed when the greenhouse humidity decreased.

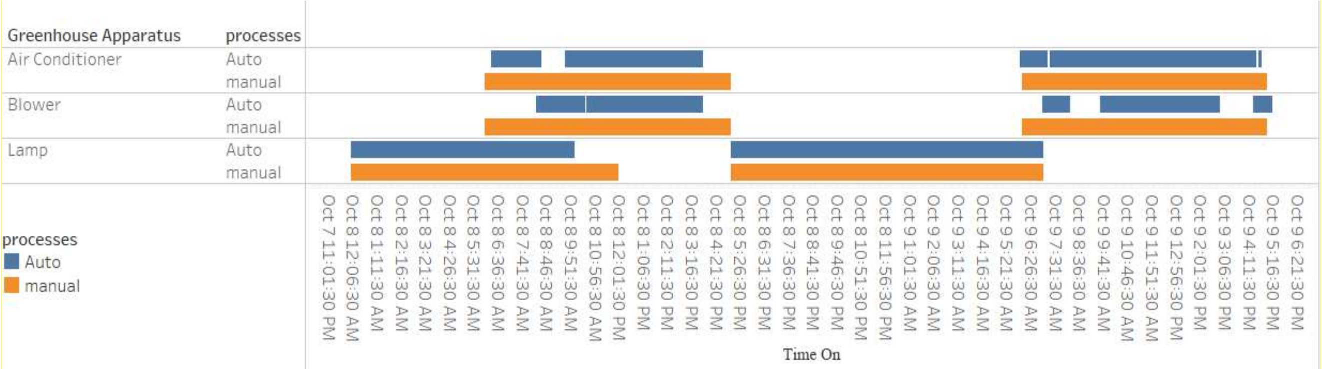

Fig. 10 Greenhouse apparatus time-on

The duration of equipment usage inside the greenhouse is relatively different compared to the previous manual method, as shown in Fig. 10. It provides an example of daily usage over two days. The data shows that the AC's usage time as a cooling system inside the greenhouse, which operates automatically, ranges from 8 hours 24 minutes to 10 hours 34 minutes per day, representing a reduction of 4%-24% compared to the manual method. On the other hand, the blower usage decreased by 32%-33% compared to the previous method. As for the usage of the lamps, there is not much change. The above data shows that the built-in system only saves 8% of lamp usage compared to the previous manual method. The calculation does not include sprinkler usage, as the manual activation time was not well recorded. The discussion above indicates that the built-in system can save electricity consumption [29].

B. Comparison of Proposed System with Previous Findings

This research focused on how automation can optimize the existing greenhouse systems for better energy efficiency. The system efficiently manages the microclimate by automating temperature and humidity control, suggesting potential electricity savings without changing the equipment. Our results show that the proposed system effectively maintained the internal temperature at around 32°C during the daytime. This method showed satisfactory results in maintaining daytime temperatures that were also in line with what was done by [35]. The temperature could be maintained between 20 and 35°C without extra energy, thus making it particularly suitable for hot climates. It also reduced water consumption significantly.

The developed system managed humidity effectively. The sprinkler pump increased daytime humidity by 15%

compared to external levels. Our results closely align with the findings of similar research conducted by [35], which found that sprayer mounting the fogging system allowed for higher relative humidity values. Many researchers [16], [25], [34] also agree that fogging systems provide an efficient cooling process that allows for adequate climate control and prevents plant dehydration and heat stress caused by high temperatures. Integrating an evaporative cooling system with natural and forced ventilation and dehumidification provides a favorable climate for better crop yields. The previous study [6] confirmed that the evaporating cooling coupled with ventilation devices (fans, e.g.) is more efficient for climate control in greenhouses in hot climates.

Our research also has revealed promising potential in enhancing energy efficiency within greenhouse operations. By leveraging existing equipment and exploiting external conditions, our method offers the possibility of significantly improving energy efficiency, estimated to range from 10% to 30%. These findings are consistent with several experimental and numerical studies conducted by experts in the field. These studies have emphasized the importance of smart cooling technologies in greenhouse environments, which, when effectively deployed, could lead to remarkable energy efficiency gains, ranging from 24% to 34%. Reducing active cooling needs by implementing efficient passive cooling and ventilation strategies has been a focal point in these studies [7].

Additionally, our research highlights the role of cooling systems and blowers in reducing energy consumption by 4% to 33% when compared to manual methods. This aligns with the broader consensus that heat pumps, for instance, can be up to 50% more efficient than traditional heating and cooling techniques[36]. Furthermore, the combination of natural ventilation, evaporative cooling, and shading, as explored in our research, has the potential to yield energy savings of 25% to 50%, mirroring the findings of experts who underscore the benefits of reducing reliance on energy-intensive mechanical cooling[35]. These concordant results across multiple studies underscore the viability of our approach and its contribution to advancing sustainable practices in greenhouse energy management.

While our study offers valuable insights into greenhouse automation, it is important to acknowledge several limitations. First, our proposed system has high initial investment and complexity in implementation. Also, the effectiveness is contingent on the accuracy and reliability of sensors and algorithms and more robust systems. Additionally, although the environmental control system inside the greenhouse can utilize the external environment to regulate temperature and humidity, it may have limitations in terms of control range. For example, if the external environment is too hot, it becomes challenging to maintain a cool temperature inside the greenhouse, requiring the cooling system to remain operational. Previous studies mentioned [13], [37] that other constraints, such as extreme temperature variations, high rainfall, strong winds, or rapid climate changes, can affect the system's ability to maintain the desired conditions inside the greenhouse.

Furthermore, several studies have established that relying on the external environment to control temperature and humidity inside the greenhouse carries the risk of introducing diseases and pests from the outside[2], [37]. Although sanitation measures and air filters can be implemented, the risk of infection and pest transmission remains when the external environment is allowed to enter the greenhouse.

IV. CONCLUSION

This study embarked on an innovative journey to revolutionize greenhouse climate control. Our primary goal was to maximize the efficiency of existing cooling and heating systems while considering external temperature and humidity conditions. The automation system we meticulously developed underwent a rigorous 30-day testing period in September 2021, during which temperatures fluctuated between 26°C and 31°C, and humidity levels spanned from 65% to 70%. Our testing revealed the potential of the automation system to bring about efficiency in utilizing greenhouse equipment. For instance, the cooling system and blowers slashed consumption by 4% to 33% compared to the conventional manual approach. Nevertheless, using lamps as heaters still requires fine-tuning, as we managed only an 8% savings compared to manual heating.

Moreover, the real-time monitoring and automatic control system, accessible through a dedicated website, facilitated continuous monitoring of temperature, humidity, and equipment status, empowering users to promptly detect anomalies or equipment malfunctions. The developed greenhouse automation system, equipped with real-time monitoring and automatic control capabilities, is promising to enhance equipment efficiency and provide tighter control over temperature and humidity. However, further improvements are essential, particularly in optimizing the use of lamps as heaters.

This research represents a significant stride in technology development aimed at bolstering the efficiency and reliability of greenhouse automation systems. While the potential to leverage the external environment for climate regulation in greenhouses is evident, it is crucial to acknowledge the associated limitations and risks. Implementing machine learning and AI-driven algorithms can facilitate future research that can adapt to varying external conditions more effectively and optimize the performance of greenhouse automation systems.

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