A study on microclimate monitoring and control inside greenhouse using fans automation

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ABSTRACT

Efficient microclimate management is crucial in enhancing crop yields in greenhouses. Factors like temperature, relative humidity, and ultraviolet (UV) index significantly impact crop quality. The absence of adequate ventilation mechanisms in greenhouses presents a challenge for temperature regulation. This study proposes a solution for tropical greenhouses by designing a system that automatically activates fans when temperatures rise above 30 °C. This system regulates temperature and cultivates optimal growth conditions for crops. It is supported by a web page that enables monitoring and adjustment of microclimate data. To accommodate individual crop requirements, the minimum temperature threshold for fan activation can be modified, enhancing the system's adaptability. The impact of the UV index on greenhouse temperature is also considered. The automation system decreases the temperature by around ±3 °C when the UV index hits 10. Nonetheless, its cooling impact wanes beyond the UV index of 10. A greenhouse automation system, equipped with fans and internet access, proves quite useful for agricultural environment management. It tackles the temperature control issue and offers varied solutions.

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1. INTRODUCTION

The use of advanced engineering methods in automating greenhouses has captured a lot of attention lately. This technology has the potential to revolutionize agricultural practices and enhance crop yields in controlled environments [1]. Greenhouses create a carefully controlled environment that can help plants thrive while also shielding them from adverse environmental conditions. This makes them a crucial tool in modern agriculture. However, in tropical regions like Indonesia, characterized by warm and humid tropical climates, maintaining ideal greenhouse conditions has become increasingly challenging, necessitating solutions due to the unique climatic conditions and environmental factors found in tropical regions [2]. Building greenhouses in tropical regions can present challenges due to the high temperature and humidity that occur annually. While greenhouses are typically constructed to retain heat, in tropical regions it can result in excessive heat that may stress or damage plants. Additionally, greenhouse microclimate conditions can create an ideal environment for pests and plant diseases [3]. Stress in plants lowers their photosynthesis ability, inhibiting growth and even causing death [4]. Furthermore, traditional greenhouse operations typically depend on manual labor, which is both labor-intensive and error-prone.

To overcome these challenges, researchers have looked into using automated systems to take care of and improve greenhouse small-scale environments. Greenhouse automation systems commonly use current technologies and methods, like sensor networks, single-board computers, and data-driven algorithms, to achieve effective and efficient climate control [5]. Greenhouse automation allows farmers to optimize crop growth, improve efficiency, and maximize yields. Automation systems for climate control, irrigation, and crop management have vast potential to revolutionize agriculture [6]. Precise monitoring of the environment is a key challenge in greenhouse automation, and many studies have investigated and addressed this issue through sensor optimization. A study conducted by Hassanien *et al.* [7] investigated how temperature and relative humidity sensors can be utilized to regulate the microclimate in greenhouses for enhanced chili production. These sensors play a significant role in identifying suitable microclimate parameters for maximizing production. However, there may be a lack of understanding regarding the types and setups of sensors that are appropriate for the specific crop requirements in diverse environmental conditions.

Moreover, the role of single-board computers (SBC) in greenhouse automation has gained significant attention recently. A study by Cardenas_Rivero *et al.* [8] and Morais *et al.* [9] investigating the integration of a microcontroller, cloud storage for data processing, and automation of control devices by linking the microcontroller to a personal computer through a universal serial bus (USB) connector for data transfer. They also utilized a liquid crystal display (LCD) screen as a means of monitoring. While these studies have demonstrated the potential of SBCs to improve the response speed and accuracy of automation, questions remain on how to select SBCs that strike a balance between performance and integration. Another research conducted by [10] presents an internet of things (IoT) based automation system for greenhouses that uses a wireless sensor network (WSN) to collect real-time data and perform control. The focus of this study's findings is optimizing greenhouse management through data-driven decision making. In a separate study, Shaikh *et al.* [11] investigated predictive maintenance in greenhouse automation and highlighted the use of machine learning and algorithm optimization to enhance the efficiency and reliability of automation systems. Although these findings offer valuable insights into greenhouse automation, a significant gap remains in the development of automation systems that can effectively regulate microclimate conditions with fans, particularly in tropical regions. Fans can be utilized in greenhouses to regulate temperature and enhance air circulation. By doing so, the heat can be evenly distributed throughout the rainy season and excess heat can be eliminated during the dry spell. The implementation of fans is projected to consistently and comfortably maintain the microclimate conditions suitable for the plants.

This research emphasizes the crucial role of SBCs, including the Raspberry Pi (RPi) and Banana Pi, in the design of a greenhouse automation system. These compact yet high-performing devices act as the system's main processing unit, overseeing data collection, analysis, and process control [12]. The RPi, which is designed with the advanced RISC machine (ARM) architecture, is widely recognized for its versatility in engineering applications. Similarly, the Banana Pi offers superior specifications, improved processing power and lower price, demonstrating potential for high performance in data-intensive tasks and cluster computing applications [13]. Sensor networks are essential for capturing environmental data such as temperature, humidity, and light intensity, providing important inputs for algorithms controlling climate. The SHT11 sensor excels in detecting temperature and humidity within a greenhouse environment [14]. Its reliable performance has been verified in studies focusing on applications like climate-controlled environments and egg incubators. Additionally, the GUVA-S12SD sensor is an effective device for measuring light intensity. It enables smart lighting control in both smart homes and agricultural settings [15].

Integrating sensors with the SBC allows for real-time data acquisition, enabling engineers and researchers to develop data-driven solutions for efficient resource utilization and climate control [16]. To optimize the automation system, the application of engineering design and development methodology is crucial, encompassing planning, designing, building, and implementing the automation system to achieve desired objectives and outcomes. Through the deployment of empirical data and dependable sensor technology, researchers can investigate more effective and expandable remedies for addressing intricate computational workloads and pushing the boundaries of distributed systems and big data processing in the domain of greenhouse automation [17], [18].

Current research aims to address this specific gap by designing a system that integrates hardware and software components to ensure precise climate control through fan automation. A major gap in the existing literature about greenhouse automation is the lack of climate control using a fan as the main microclimate method. Existing research in greenhouse automation has laid the groundwork for improved agricultural practices. While numerous studies have explored the integration of different technologies and strategies, there remains a research gap in the area of automated fan climate control. This study aims to bridge this gap by developing an automation system that provides a solution for maintaining an optimal microclimate in greenhouses. The integration of advanced technologies, including IoT and cloud-based solutions, contributes to the evolution of greenhouse automation systems and their potential impact on sustainable agriculture.

This includes not only fan redundancy, but also adaptive control logic and monitoring systems to ensure that crops are protected from the effects of tropical region heat.

2. METHOD

The research was conducted in a greenhouse located at Universitas Padjadjaran, Jatinangor District, Sumedang Regency, West Java, Indonesia at latitude 6°55'14.2"S and longitude 107°46'27.7"E. The automation system's technical section is built using Banana Pi M2 Berry (BPi), an SBC that has an Allwinner A40i system-on-a-chip (SoC) with a quad-core processor and 1 GB of random access memory (RAM), furthermore this SBC has integrated wireless fidelity (Wi-Fi), Bluetooth, four USB 2.0 ports, one MicroUSB port, high-definition multimedia interface (HDMI) port, audio jack and one serial advanced technology attachment SATA port [19]. The SHT11 sensor for air temperature and relative humidity, along with the GUVA-S12SD sensor for measuring the ultraviolet (UV) index are utilized as data inputs. Relays and fans serve as output devices. The decision to use BPi over RPi was based on its lower price. Although both single-board computers share similar design structures, adjusting the system for BPi required additional commands and techniques to improve its functionality. Breadboards, jumper cables, and Duradus were selected as components to enhance the efficient connection and protection of electronic elements [20].

2.1. Analysis

The working principle of the proposed device is to monitor temperature, relative humidity and light intensity, and control the fan through a relay when the measurement results show values above the threshold. In addition to monitoring and controlling, the system will also send data to a web server via Wi-Fi. The data stored on the server is presented on a web page that can be accessed by the user using an internet-connected device as shown in Figure 1. The selection of the minimum and maximum number of fans for a greenhouse depends on a number of factors, primarily the size of the greenhouse, the external environmental conditions and the specific crop requirements. For smaller greenhouses or those with moderate temperature fluctuations, a single fan may be sufficient as the minimum requirement to maintain effective temperature control. However, in larger greenhouses or environments with greater temperature fluctuations, multiple fans may be required to distribute cool air evenly and prevent heat build-up. This greenhouse automation system has been designed with the flexibility to adapt the fan configuration to the specific needs of the greenhouse. In this research we are using two MPHF1000 12" fans. The choice of two MPHF1000 12-inch fans for heat dissipation was motivated by their ability to maintain stable greenhouse operating conditions. These components were chosen for their compatibility with the system objectives.

The diagram shown in Figure 1 illustrates two sections, the technical section and the information section. In the technical section, sensors detect microclimate conditions within the greenhouse. The data collected is then processed in the SBC to determine whether the relay should be turned on. Additionally, in the information section, the SBC transmits data via Wi-Fi to the server to store microclimate data in the database and present it to the user via a web interface. In the information section, we employ bootstrap as our framework for constructing a user-friendly front end. On the back end we utilize MySQL database management system (DBMS) to store all transmitted data [21]. Lastly, we implement PHP for information presentation [22]. All website information is accessible through https://gadjah.net/auto to users with internet-connected devices. Putty was used for remote access to the SBC, and to aid in remote system administration and operation. Python 3 was selected as the primary programming language for technical section protocols to guarantee smooth coordination and communication among hardware components [23]. The integration process of BPi presents unique challenges owing to its relatively unexplored nature in comparison to RPi. Overcoming these challenges mandates extensive research and code development. However, one can seamlessly address them by harnessing the advantages of BPi and effecting adjustments.

Furthermore, the absence of a specific BPi ecosystem raises concerns about the ease of integration into automation systems. It is crucial to emphasize that while the integration process requires careful attention, it can still be streamlined for future implementations. Simplifying the SBC selection process is also important to ensure wider accessibility and ease of adoption. Future versions of the greenhouse automation system may consider using SBCs with more easily accessible resources and a user-friendly interface. While the BPi presents distinct benefits regarding its performance and competitive pricing, it is imperative to consistently assess the equilibrium between these advantages and the potential intricacies it could add to the integration process.

2.2. Design

The automation system design was carried out using the engineering design and development methodology that involved several stages, namely the conceptual design phase, equipment programming phase, assembly phase, and equipment testing phase [24]. The selected SBC for this system is the BPi, a competitor product of the RPi SBC. The programming aspect of the BPi uses a similar coding structure with the RPi;

however, certain additional commands are required to ensure proper functionality of the programs. Moreover, limited online resources and forums for programming with the BPi pose further difficulties for developers seeking guidance in optimizing their codes and projects. Addressing these challenges in the integration and programming of the BPi requires research, and problem-solving code development. By leveraging the system's advantages and implementing strategic adaptations, researchers can ensure seamless functionality and performance optimization, ultimately yielding a robust and efficient automation solution. Moreover, knowledge sharing and community engagement can foster a collaborative environment, enabling developers to exchange valuable insights and collectively overcome the hurdles posed by the relatively less explored BPi platform.

The greenhouse automation system has been designed in two main sections: the technical section and the information section, as illustrated in Figure 1. The technical section's primary objective is to gather and process microclimate data within the greenhouse. They are responsible for deploying various sensors to acquire real-time information about the greenhouse's microclimate, including temperature, humidity, and UV index. The technical aspect involves deploying a network of strategically positioned sensors across the greenhouse to facilitate data collection. These sensors operate as the components responsible for acquiring data, transmitting essential information to the BPi as a central processing unit, for the purposes of analysis and data processing. Algorithms are executed on the SBC to conduct data fusion for generating insights about the greenhouse's microclimatic conditions. Contrarily, the information segment functions as the control center and user interface for the automation system of the greenhouse. A user-friendly and informative visual representation of the collected data from the field segment is provided. Web-based applications or dedicated software are used to present the data, allowing stakeholders to conveniently access and remotely monitor the greenhouse's microclimate.

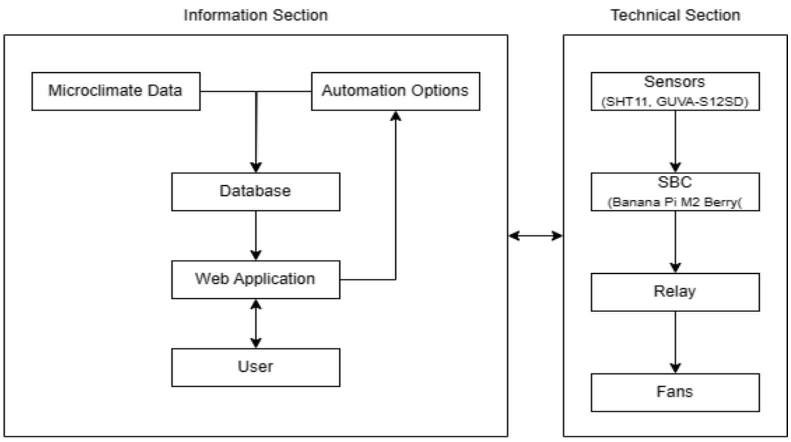

Figure 1. Automation device architecture

The information section includes user-friendly graphic interfaces that show real-time and past trends. This helps make informed decisions for greenhouse management. Based on the data insights, farmers can adjust and fine-tune environmental parameters to optimize crop growth conditions and resource utilization. Control capability extends to managing cooling systems, irrigation schedules and ventilation mechanisms to achieve a precise and efficient microclimate management system. The technical and information sections seamlessly integrate to create a greenhouse automation system, empowering agricultural practitioners to make data-driven decisions and improve crop productivity. The use of internet-enabled features allows for remote data access and control, enabling precise and responsive greenhouse climate management from anywhere with an Internet connection. This integration represents an advancement in precision agriculture and contributes to sustainable food production.

The configuration of this greenhouse automation system comprises the BPi as the SBC, along with the GUVA-S12SD sensor, SHT11 sensor, and relay components. The GUVA-S12SD and SHT11 sensors are directly interfaced with the SBC, while the relay is connected to the fans, enabling automated fan operation when the SHT11 sensor detects a temperature above 30°C. The energy source for the fans is supplied through the electrical power grid. The developed automation system is designed to be Internet-enabled, facilitating data visualization through a dedicated website. Additionally, the system's automation control can be accessed and managed remotely using mobile devices or laptops with Internet connectivity via wireless connection.

The selected BPi serves as the central processing unit, orchestrating data acquisition and processing from the GUVA-S12SD and SHT11 sensors. These sensors provide real-time feedback on UV index and temperature levels, respectively. The relay component acts as a switch to control the fans based on the temperature data received from the SHT11 sensor. When the temperature exceeds the defined threshold (30 °C), the relay triggers the fans to activate automatically, mitigating heat build-up within the greenhouse environment. To ensure continuous power supply to the fans, an electrical connection is established to the main power grid. This setup enables the fans to operate efficiently and maintain optimal microclimate conditions within the greenhouse.

The automation system is designed with Internet connectivity in mind, allowing seamless data transmission to a dedicated website. Stakeholders can access this website to view real-time and historical data trends, enabling informed decision-making for greenhouse management and optimization. Furthermore, the implementation of mobile and notebooks compatibility with wireless connectivity empowers users to remotely access and control the automation system. This flexibility facilitates convenience and enables timely adjustments to environmental parameters, ensuring precise and responsive greenhouse climate management from anywhere with an Internet connection. Figure 2 illustrates the seamless integration of technologies within this automation system, Algorithm 1 shows the automation algorithm used in the study in the form of pseudocode.

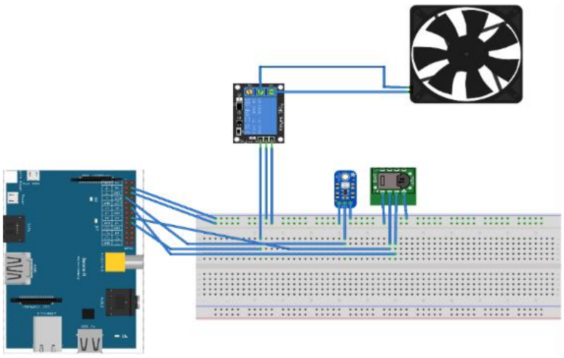

Figure 2. Diagram of the constructed automation system

Algorithm 1. Pseudocode for sending and receiving microclimate data
```
import sht library
check if (serial port) is not ready
 refresh

loop while serial port is connected:
 acquire sht11 temperature in Celsius
 acquire sht11 relative humidity in Percent
 acquire guva-s12sd uv as index

 check if (temperature or humidity or uv not a number):
 write "Check sensor: Run-time error"

 send temperature data
 send relative humidity data
 send uv data
 sleep 60 seconds

database connection
set date and time (now)

convert time to unix time

select latest microclimate data
loop while accessing micrOlimate table:
 get unix time and convert to list
 get temperature and convert to list
 get humidity and convert to list
 get uv index and convert to list

display microclimate data on page
```

3. RESULTS AND DISCUSSION

The greenhouse automation system was developed around the utilization of the BPi SBC device, with remote access facilitated through the Putty application. The primary objective of this research was to establish a system that could effectively control the microclimate within the greenhouse, specifically by autonomously regulating temperature using a fan. The system was designed to enable real-time microclimate monitoring through a website interface. The developed automation system’s main objective is to monitor and fine-tune the operation of fans to maintain temperature levels within the desired range. The BPi was programmed to accomplish this task automatically, ensuring that the greenhouse environment remained stable and ideal to optimum crop growth. Remote access to the system was provided through the Putty application, allowing users to maintain automation performance, monitor real-time climate data, and make necessary adjustments as needed.

The data obtained from the greenhouse's microclimate is then transferred to a MySQL database, which has been installed into the SBC infrastructure. This connection enables the presentation of the accumulated data on the website, enabling the presentation of accumulated data on a user-friendly website, serving as a central hub for managing the greenhouse's fan functions. Users could customize the fan's minimum operational temperature based on the specific requirements of their cultivated crops and the greenhouse environment, ensuring efficient fan operation within the targeted temperature range. The automation system was built using Python for the control logic and communication between the SHT11 sensor and the SBC, while PHP was used to develop the website, which provides an interactive and user-friendly interface for viewing the climate data. The reliable SHT11 temperature and humidity sensor played a crucial role in providing accurate climate data. When the temperature exceeded the pre-set threshold of 30 °C, the sensor triggered the automation of the fan operation.

The SBC, which acts as the automation system's central processing unit, was developed using the BPi. It received temperature readings from sensors and, based on a pre-defined algorithm, activated a relay which in turn initiated the operation of the fan. This relay acted as a switch, allowing the SBC to effectively control the operation of the fans. The fans were programmed to run for 60 seconds when activated, helping to reduce the temperature inside the greenhouse, ensuring that the greenhouse maintained an optimal climatic environment was a fundamental aspect of the automation system. The automated system enabled prompt activation of greenhouse control procedures when temperatures surpassed the preset threshold of 30 °C, protecting the plants from the effects of heat and creating a nurturing environment ideal for their growth.

Data management and integrity were essential to the automation system built. The BPi processed and transmitted the collected microclimate data to the designated database, which acted as a centralized repository for gathering environmental data. Error handling mechanisms were integrated into the automation system to validate data uploads and offer feedback in case of errors by implementing the 'IF' statement to make logical decisions based on the temperature readings in the greenhouse. When the temperature exceeded the pre-set threshold of 30 °C, the 'IF' condition was met, resulting in the activation of the fan control logic. The relay, acting as an electromechanical switch, enabled the SBC to initiate fan operation. To ensure effective cooling, the fans were programmed to run for exactly 60 seconds, allowing proper heat dissipation and a timely response to temperature changes. Within one minute intervals, the system continuously monitored the temperature and relative humidity conditions in the greenhouse. If the temperature exceeded 30 °C, the relay would reset and the fans would restart in an attempt to stabilize the temperature.

The web application was developed using a combination of hypertext markup language (HTML), PHP, and MySQL programming languages. HTML provided the basic framework for creating web pages, while PHP maintained dynamic content and interacted with database systems built with MySQL. The web page had two separate pages: one showing microclimate conditions in the greenhouse, and the other for automation configurations. Presentation of microclimate data prioritized displaying the most recent observations in descending order, for users are able to get updates easily. The second page of the website acted as a control panel, allowing users to set the minimum temperature threshold to trigger the automation system. PHP processed user input and updated the database, allowing minimum processing temperatures to change in real time. Users can access real-time microclimate data, analyze trends, and control the automation systems, all through a web-based interface [25].

3.1. Analysis of microclimate data in a greenhouse environment

Table 1 presents the 20-day results of environmental variables collected in the greenhouse; the monitoring variables were temperature (°C), relative humidity (RH %), and UV index. Furthermore, Figure 3 offers a visual representation of daily data on greenhouse microclimate conditions. These three charts display alterations in microclimate parameters inside the greenhouse and demonstrate their interdependent connection, serving as a crucial resource for assessing greenhouse microclimate and comprehending shifts in these parameters over time. Greenhouse microclimates have a significant impact on crop production efficiency [26]. Understanding and managing these environmental factors is important to ensure favorable conditions for crop diversity and growth [27].

Table 1. Microclimate data acquired through automation devices in the greenhouse

ID	Temp (°C)			RH (%)			UV		
	Max	Min	AVG	Max	Min	AVG	07	12	17
1	38	21	29.2	82	50	65.3	1	10	3
2	37	22	29.3	81	53	67.3	1	10	2
3	37	21	29.8	81	59	67.0	1	10	3
4	38	19	33.6	88	51	64.7	0	10	2
5	36	21	28.5	82	57	67.7	1	10	1
6	36	22	29.5	86	58	68.3	1	10	2
7	32	20	28.2	84	51	68.3	1	10	3
8	35	20	29.3	86	51	66.3	3	10	3
9	37	22	29.5	87	52	67.0	4	10	4
10	39	25	32.3	82	58	65.7	3	11	5
11	36	21	30.3	84	57	66.3	3	10	3
12	39	23	33.9	84	53	64.7	4	11	3
13	38	22	33.8	85	51	64.3	3	11	5
14	39	22	34.2	87	52	65.0	4	11	4
15	39	22	35.5	88	53	62.7	3	11	5
16	39	23	36.7	84	54	63.7	4	11	6
17	37	24	34.2	81	55	64.0	4	11	4
18	39	25	34.7	85	52	61.3	5	11	6
19	41	25	35.6	80	51	61.7	6	12	5
20	42	24	38.2	79	50	61.3	5	12	6

3.1.1. Temperature variation

Analyzing the temperature data in Table 1 and Figure 3(a), significant daily temperature variations were observed. Daily maximum temperatures ranged from 32 °C to 42 °C, and daily minimum temperatures ranged from 19 °C to 25 °C. Specifically, the highest recorded temperature of 42 °C was observed on the 20th, while the lowest temperature was 19 °C on the fourth day. These findings indicate that the use of two fans is not sufficient in reducing ambient temperature, especially when the UV index reading is above 10 and highlights the importance of effective insulation in greenhouses, as extreme temperatures can harm plant growth [28].

3.1.2. Humidity levels

The relative humidity (RH %) data, as shown in Table 1 and Figure 3(b), reflect changes in the greenhouse moisture content. The observed humidity ranged from 50% to 79%. While this area is still acceptable for most crops, it needs to be monitored more frequently because high humidity can cause fungal diseases and low humidity can cause plant distress and humidity control is important to maintain optimal growing conditions.

3.1.3. UV index

UV index data in Table 1 and Figure 3(c) show that greenhouse UV levels are measured at 07:00, 12:00, and 17:00 daily. UV radiation can have negative effects on plant health, including leaf damage and water-deprived plants [29]. The recorded UV index readings vary from 1 to 12, and the highest observed value during the day was 12, indicating potential harmful UV radiation. Safety measures such as UV screens or shade nets can be used on greenhouse roofs when possible.

3.2. Microclimate management

Microclimate data collected in the greenhouse over a period 20 days has provided insights into the changes in environmental conditions, temperature, humidity and light intensity. These variables have implications for the greenhouse environment and planted crops, and therefore require management. Some things that need to be addressed are:

3.2.1. Temperature control

With temperatures reaching 42 °C on hot days, an air temperature control mechanism needs to be added to avoid stress on plant growth. What can be done is to increase the number of fans or enlarge the diameter of the fan to facilitate air circulation. Or by adding an air conditioner to accelerate the drop in air temperature with the consequence that the humidity value will also drop [30].

3.2.2. Humidity regulation

Although the relative humidity of the air in the greenhouse still has a range that can be tolerated by plants, it must still be monitored. That, to avoid extreme increases or decreases in humidity at unpredictable times that can impact the appearance of fungi or stress plants. The use of dehumidifiers to reduce humidity or fogging to increase humidity can be done to maintain the balance of humidity levels in the greenhouse [31].

3.2.3. UV protection

Fluctuations in UV index values indicate that it is necessary to protect plants, especially those that are sensitive to light. The easiest protection is of course by using a shade that can cover the top of the greenhouse when the sun is shining brightly and open automatically when the UV index decreases to a certain limit. It is also necessary to replace the sensor with a better one such as the BH1750 type so that the measurement value has a wider range so that data management and control configuration become more flexible.

3.2.4. Data-driven decisions

The microclimate data collected highlights the importance of data-driven decision making in greenhouse management. Regularly monitoring and analyzing environmental conditions can help identify patterns and trends that can be used for early adoptions. Based on data analysis, it is possible to improve crop performance and productivity by following appropriate greenhouse management practices [32].

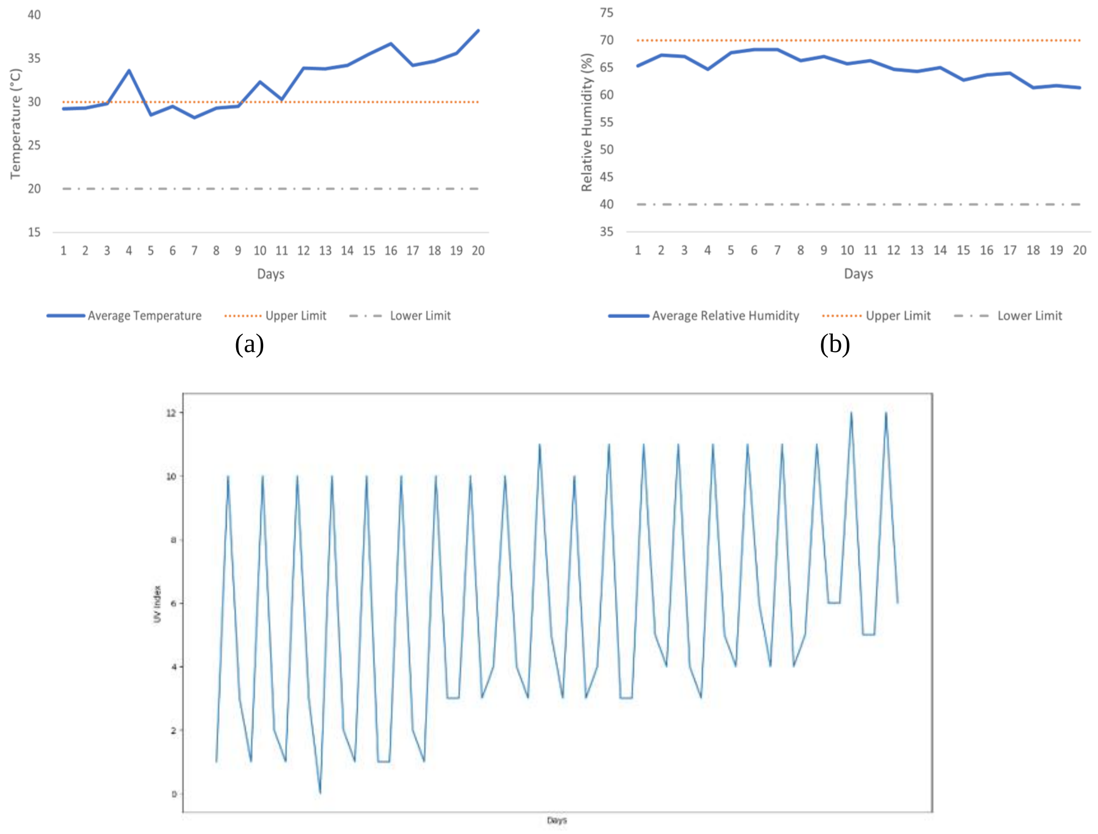

Figure 3. Daily microclimate data acquired through fans automation; (a) average temperature, (b) average relative humidity, and (c) UV index

3.3. Strategies for addressing operational challenges in greenhouse automation

With regard to the management of operational instability in greenhouse automation systems, this research acknowledged the importance of addressing this important aspect. Ensuring the reliability and robustness of the system, especially in the face of unforeseen challenges, is paramount. Here are some ways to deal with operational instabilities:

3.3.1. Monitoring and diagnostics

Operational instabilities can arise from a variety of sources, including sensor malfunctions, network interruptions or unforeseen environmental factors. To effectively manage such situations, the greenhouse automation system is equipped with a monitoring framework. Real-time data from sensors, SBCs and automated components is continuously collected and analyzed.

3.3.2. Immediate alerts and notifications

In the event of operational instability, the system is still not designed to provide immediate alerts and notifications to relevant stakeholders. An ideal automation system will have alerts, which can be in the form of email notifications, short message service (SMS) messages or mobile app notifications, to ensure that relevant personnel are informed immediately. For example, if a sensor reports an abnormally high temperature or there is a loss of communication with a critical component, our system triggers alerts to notify greenhouse operators or maintenance teams.

3.3.3. Redundancy and failover mechanisms

To increase system reliability, we have implemented redundancy and failover mechanisms. Redundant sensors and SBCs are strategically placed throughout the greenhouse to ensure that data continues to be collected even if one sensor or SBC experiences a problem, minimizing downtime and disruption. In the event of a fan malfunction or failure, the automation system is designed to respond actively. The system logic includes a mechanism to immediately activate the remaining operational fan. This redundancy ensures that the greenhouse's cooling capacity is not compromised in the face of unexpected fan problems.

3.3.3. Data-driven analysis

Operational instabilities often leave valuable data trails. By examining historical data, patterns and sensor readings leading up to an instability event, insights can be gained and root causes traced. This approach helps to refine automation algorithms and take proactive measures to prevent similar instabilities in the future.

Empowering users to manage operational instability requires a dedicated troubleshooting interface. Users can access detailed logs, error reports and diagnostic tools directly from the interface. This user-friendly approach enables field personnel to quickly identify and resolve problems. Operational instability is seen not just as a challenge, but as an opportunity for improvement by maintaining a feedback loop that encourages users and maintenance teams to report and document any instability incidents. Such feedback is invaluable in refining system performance and improving resilience. The management of operational instability is an integral part of the design and operation of any greenhouse automation system. We have implemented just a few of many multi-faceted approaches such as real-time monitoring, redundancy, and data-driven analysis. Through continuous improvement and collaborative problem solving, the system not only deals effectively with operational instability, but also evolves to become increasingly robust and reliable.

3.4. Future directions

In future research, further enhancements to the automation system can be explored. This could involve using advanced data analytics and machine learning algorithms to predict and react to microclimate changes preemptively. Also, integrating additional sensors to monitor soil moisture and carbon dioxide (CO_2) levels could provide a more comprehensive view of the greenhouse environment. The automated greenhouse system has effectively demonstrated the regulation of temperature and microclimate control within the greenhouse. The information gathered provided valuable insights into the greenhouse environment, highlighting the importance of effective temperature, humidity and UV index control strategies. By using information gathered from data, managers of greenhouses can make better decisions to help their crops grow better and maintain a greenhouse that works in an efficient and sustainable way.

An alternative, simpler approach was also highlighted for future direction by recognising the value of considering alternative SBC options. The RPi, a widely recognised and well-documented SBC, offers a compelling alternative. Its extensive community support, vast online resources and established ecosystem can simplify integration tasks and speed up the development process. Future research and development efforts could include a comparative analysis of SBCs, weighing their advantages against integration complexity to determine the most suitable option for specific greenhouse automation applications. Simplifying the integration process is consistent with the overall goal of improving the user experience. A simpler and more intuitive integration experience can enable a wider range of users, including farmers with different technical backgrounds, to adopt and benefit from greenhouse automation technologies. In the spirit of user-friendliness, improving accessibility means not only simplifying the integration process, but also providing comprehensive documentation and support, and empowering a diverse user base, including farmers with different technical backgrounds, is paramount to the success and widespread adoption of a technology. Collaboration within the engineering and automation community is also important to facilitate easier integration. Sharing insights, best practices and experiences can collectively contribute to the development of user-friendly automation systems. Engaging with the community and seeking input from experts in the field will be an integral part of this collaborative approach.

4. CONCLUSION

The automation system's effectiveness in maintaining a controlled microclimate within the greenhouse environment is demonstrated by the results obtained. The system provides a reliable and efficient solution to manage the greenhouse climate by automatically regulating the temperature based on predefined thresholds. The data shows the impact of UV radiation on the greenhouse temperature. Reducing the temperature is challenging, especially within the range of 10 to 12, due to high UV index values. Significant cooling effects are challenging to achieve due to intense solar radiation contributing to elevated temperatures within the greenhouse. During periods of lower UV index values below 8, the system offers better temperature control capabilities, providing a more suitable environment for plant growth. An inherent advantage exhibited by the advanced automation system lies in its remarkable customizability. Users are afforded the capability to personalize the minimum operational temperature, thereby aligning it with the distinct requisites characteristic of various plant species. This adaptable trait renders the automation system amenable to an extensive array of crops, each delineating its own set of climatic predilections. Consequently, this system bestows a multifaceted remedy for greenhouse cultivation, one that accommodates the exigencies of diverse botanical varieties while concurrently refining their cultivation milieu. Nonetheless, the formulation of the automation system utilizing the BPi necessitates an additional degree of endeavor. While the fundamental commands retain their constancy, the system necessitates meticulous fine-tuning and supplementary configurations to ensure an optimal performance threshold. Notwithstanding this, upon meticulous calibration, the BPi proffers a dependable platform for the efficacious realization of the automation system. The implemented automated system stands as a proficient instrument for the administration of greenhouse facilities, proficiently overseeing and governing optimal greenhouse thermal conditions. Evidently, the UV index exercises discernible influence over greenhouse temperatures, thereby underscored the significance of adaptable strategies during phases characterized by heightened solar radiation. The system's malleability and array of customization alternatives render it a versatile resolution amenable to the diverse climatic prerequisites associated with a myriad of botanical species. Notwithstanding the supplementary configuration demands incumbent upon the BPi, it functions as a dependable foundation for the deployment of said automated system. On the whole, this mechanized system proffers auspicious prospects for the advancement of horticultural practices within greenhouses, subsequently facilitating the attainment of refined crop cultivation and heightened productivity levels.

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