International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Fuzzy Mamdani Smart Control for Optimizing Melon Growth in Nutrient Film Technique (NFT) Hydroponic Greenhouse

Rizal Tjut Adek [1], Munirul Ula[2], Bustami[3], and Emmia Tambarta Kembaren[4]

Submitted:14/03/2024 **Revised**: 29/04/2024 **Accepted**: 06/05/2024

Abstract: The aim of the project is to create and apply an advanced control system using Fuzzy Mamdani to enhance the growth of melons in NFT hydroponic systems within intelligent greenhouses. The system is engineered to autonomously adjust temperature, humidity, pH and nutrient concentration through the utilization of sensors and actuators that are governed by microcontrollers. During a 30-day experiment, the Fuzzy Mamdani system demonstrated superior performance in comparison to the manual control system utilizing an on/off mechanism. The findings demonstrate that the Fuzzy Mamdani system effectively preserves the stability of environmental parameters, resulting in reduced fluctuations. This, in turn, has a beneficial influence on the growth and quality of melons. The temperature and humidity are maintained within the appropriate range, while the utilization of resources like as water and energy becomes increasingly efficient. Furthermore, the implementation of this approach results in melons exhibiting enhanced development uniformity and superior fruit quality. The research findings indicate that the implementation of Fuzzy Mamdani-based control systems has the potential to enhance agricultural output and quality, while also promoting the adoption of more sustainable agricultural methods.

Keywords: *Fuzzy Mamdani, Smart Greenhouse, NFT Hydroponics, Melon Growing, Control Systems*

1. Introduction

Optimal plant growth is an important factor in modern agriculture, especially in efforts to meet increasing food needs [1]. One method that is increasingly popular is the hydroponic system, which allows plants to grow without using soil, but by utilizing a nutrient solution that is given directly to the plant roots [2]. The advantages of hydroponic systems include better control over plant nutrition, more efficient use of air, and reduced risk of soil disease [3]. However, optimizing plant growth in a hydroponic system is not without challenges. Environmental variations such as temperature, humidity, pH, and nutrition must be maintained within optimal ranges to ensure maximum plant growth [4].

Smart greenhouse systems offer a solution to the challenge of controlling the plant growth environment [5]. By utilizing sensor and automation technology, smart greenhouses can monitor and control various environmental parameters in real-time [6]. This system allows more precise regulation of the conditions required by plants, thereby increasing agricultural efficiency and productivity [7].

Smart greenhouses as shown in Figure 1 also have advantages in terms of resource efficiency. With automatic control of water, energy and nutrient use, these systems can significantly reduce resource consumption [8]. This is especially important in the context of agricultural sustainability, considering global challenges related to water and energy scarcity [9].

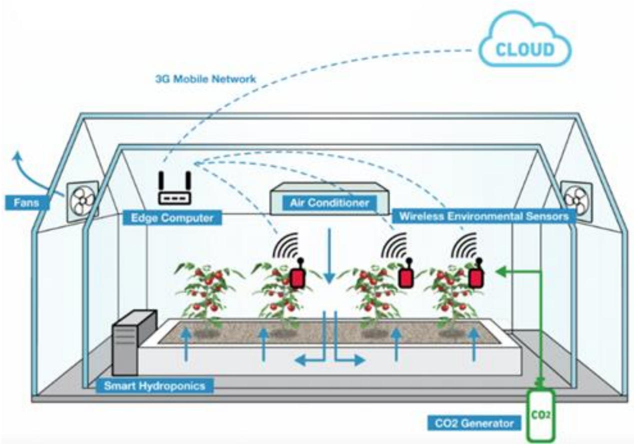

Fig 1. Smart Green House Design

One promising approach in smart greenhouse control systems is the application of fuzzy logic. Fuzzy logic allows handling uncertainties and variations in environmental data, which are often difficult to overcome with conventional control methods [10].

Fuzzy Mamdani, as one of the methods in fuzzy logic, offers flexibility and reliability in designing intelligent control systems [11]. By using if-then rules based on experience and expert knowledge, the Fuzzy Mamdani-based control system can make better decisions in managing the plant growth environment [12].

This research aims to develop an intelligent control system based on Fuzzy Mamdani to regulate the melon growth environment in an NFT hydroponic system in a smart greenhouse [13]. By focusing on increasing the productivity

[1,3]Informatics, Universitas Malikussaleh, Lhokseumawe, Aceh, Indonesia
[2]Information Technology, Universitas Malikussaleh, Lhokseumawe, Aceh, Indonesia
[4]Agribusiness, Universitas Malikussaleh, Lhokseumawe, Aceh, Indonesia

and quality of melon crops, reducing resource consumption, as well as testing and validating the performance of the control system being developed, it is hoped that this research can make a significant contribution to the development of more efficient and sustainable agricultural technology [14].

Controlling the environment in a greenhouse is a complex challenge because various environmental parameters interact with each other and have a direct impact on plant growth [15]. Parameters such as temperature, humidity, pH, and nutrition must be maintained within optimal ranges to ensure healthy and productive plant growth. Uncontrolled variations in these parameters can cause stress in plants, reduce the quality and quantity of crop yields, and increase the risk of disease [16].

Conventional control systems are often not adaptive enough to handle dynamic environmental variations in greenhouses [17]. Rigid and unresponsive control methods can lead to inefficiencies in resource use and suboptimality in plant growth [18]. As technology develops, the need for more adaptive and efficient control systems is increasingly urgent [19].

Fuzzy logic-based control systems offer a potential solution to this problem [20]. With the ability to handle uncertainty and complex variations, fuzzy logic can provide smoother and more responsive control to changing environmental conditions [21]. Adaptive systems like this can optimize the use of water, energy and nutrients, thereby not only increasing plant productivity, but also supporting the sustainability of greenhouse operations [22].

This research aims to develop an intelligent control system based on Fuzzy Mamdani to regulate the melon growing environment in the NFT hydroponic system in a smart greenhouse, increasing the productivity and quality of the melon harvest by precisely controlling environmental parameters such as temperature, humidity, pH and nutrients, reducing resource consumption. power such as water and energy by managing their use efficiently according to plant needs, and testing and validating the performance of the control system developed through field experiments to evaluate success in achieving growth targets and resource efficiency. It is hoped that this research can make a significant contribution to the development of agricultural technology, especially in the field of greenhouse environmental control. By introducing a Fuzzy Mamdani-based control system, this research can pave the way for the application of smarter and more adaptive technology in managing plant growth environments. More efficient use of resources will also support more sustainable agricultural practices, reduce environmental impacts and increase profits for farmers. This research aims not only to increase yields in the short term, but also to provide long-term, sustainable solutions for modern agriculture.

2. Material and Method

The setups of the internet of things fuzzy Mamdani control system, greenhouse and melon platforms are illustrated in Figure 1. This research uses a quantitative approach with an experimental design to develop and test a Fuzzy Mamdani-based control system in a smart greenhouse to optimize melon growth in an NFT hydroponic system in tropical areas.

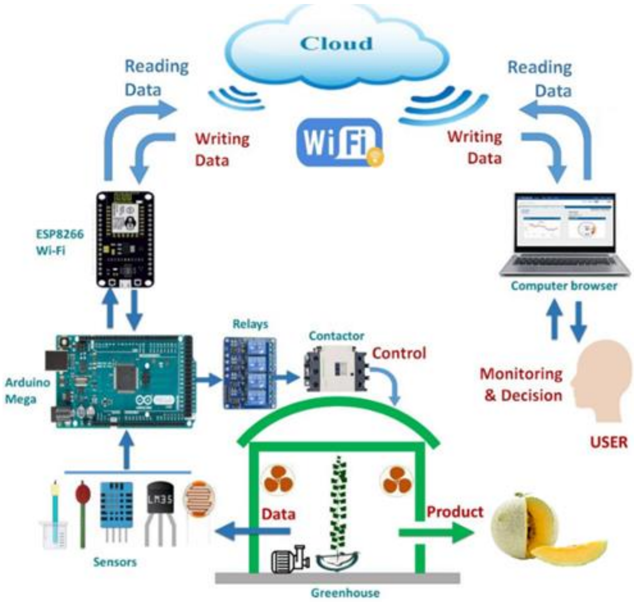

Fig. 2. The setups of the IoT Fuzzy greenhouse control system

The general scheme of the control system includes several main components: sensors for measuring environmental parameters such as temperature, humidity, pH and nutrient levels; microcontroller to process data from sensors and run the Fuzzy Mamdani algorithm; actuators to control devices such as ventilation fans, pH Up pump, nutrient pumps, and coolers fan; as well as a monitoring system to display real-time and historical data.

Description of Hardware and Software Used

Hardware:

- Sensors: DHT22, BH1750, TDS Sensor
- Microcontroller: Arduino Uno
- Actuators: Ventilation Fan, AB Mix nutrient Peristaltic pump, pH Up

Software:

- Arduino IDE: For control software development
- Fuzzy Logic library on Arduino: For implementing fuzzy logic
- Web Applications as an IoT Platform: For data visualization

Research Workflow

1. Parameter Identification: Determine the environmental parameters that are important for melon growth.
2. Fuzzy Set Design: Develop fuzzy sets and rules based on expert knowledge.
3. System Implementation: Build the system with the necessary hardware and software.
4. System Testing: Test the system under different environmental conditions.
5. Data Analysis: Evaluate control system performance and optimize based on findings.
6. Validation of Results: Validation of the system through field experiments and data analysis.

Fuzzy Rules

Control System Design Using Fuzzy Mamdani

Definition of Fuzzy Set:

- Inputs:
  - Temperature: Low, Medium, High
  - Humidity: Low, Medium, High
  - pH: Low, Medium, High
  - Nutrient Concentration: Low, Medium, High
- Outputs:
  - Fan Speed: Low, Medium, High
  - pH Up pump: Low, Medium, High
  - Nutrient pump Flow Rate: Low, Medium, High
  - Cooling Power: Low, Medium, High

Fan Speed:

- High Temperature (>30°C) OR High Humidity (>70%) → Fan Speed = High
- Medium Temperature (24°C - 30°C) AND Medium Humidity (60% - 70%) → Fan Speed = Medium
- Low Temperature (<24°C) AND Low Humidity (<60%) → Fan Speed = Low

Nutrient Flow Rate:

- High Nutrient Concentration (>1260 ppm) → Nutrient Flow Rate = Low
- Medium Nutrient Concentration (1050 - 1260 ppm) → Nutrient Flow Rate = Medium
- Low Nutrient Concentration (<1050 ppm) → Nutrient Flow Rate = High

Cooling Power:

- High Temperature (>30°C) → Cooling Power = High
- Medium Temperature (24°C - 30°C) → Cooling Power = Medium
- Low Temperature (<24°C) → Cooling Power = Off

pH Adjustment:

- High pH (>6.2) → Add Acid (Reduce pH)
- Medium pH (5.8 - 6.2) → Stable pH (No change)
- Low pH (<5.8) → Add Base (Raise pH)

2.1 User Interface

We utilized Arduino C programming language to develop the software system, specifically targeting the microcontroller Arduino Uno. Arduinos platform was utilized for component encoding with the objective of facilitating code writing.

The Arduino IDE is a concise yet comprehensive source code editor. The toolbar provides access to all programming features.

The webpage for the proposed greenhouse environmental management system enables remote monitoring and control of environmental factors, including as temperature, humidity, pH, and nutrients, from any location using the Internet. The development of this web page was carried out using Apache NetBeans, Apache2, PHP, and MySQL databases. To schedule the activation and deactivation of cooling fan, pH and Nutrition pumps and other settings, utilize the "cron job".

2.2 Data Collection and Analysis

The research's planning and implementation phase take place in the Laboratory of Informatics Engineering, University of Malikussaleh, Bukit Indah. The field testing phase take place at the Blang Tingkeum greenhouse melon hamlet in Bireuen.

System Testing Procedures

- Preliminary Preparation: calibrate sensors and ensure hardware connections.
- Data Collection: collect environmental data and control system responses every 15 minutes for 4 weeks.
- Testing for Variations in Environmental Conditions: test the system under various conditions of temperature, humidity, pH, and nutrient concentration.

This study assessed multiple parameters to determine the efficacy of the control system. The environmental parameters that are measured include temperature, humidity, pH, and nutrient concentration. Furthermore, measurements of plant growth, such as the vertical dimension of the plant and the quantity of foliage, are also documented.

Various techniques are employed for data analysis. Descriptive statistics are employed to examine the patterns and reactions of control systems. In order to assess the differences in plant performance between circumstances with and without fuzzy control, statistical tests such as T-test or ANOVA are conducted. Data visualization tools, such as graphs and tables, are employed to present data in a clear and efficient manner, hence aiding the interpretation of results.

2.3 IoT System Design for Greenhouse Environmental Control and Hydroponic Regulation

To build an IoT system that monitors and regulates the greenhouse and hydroponic system environment, the entire system is divided into three main components: (a) sensor subsystem, (b) feedback loop, and (c) actuator system.

The sensor subsystem includes various sensors designed to measure and transmit data related to important parameters, such as temperature, humidity, TDS (Total Dissolved Solids), and pH, to an Arduino controller. The selection of sensors takes into account factors such as cost, accuracy, interface compatibility, and ease of integration. These sensors interface with the Arduino hardware and are programmed using the Arduino integrated development environment (IDE). Calibration of these sensors involves rinsing with distilled water. Each sensor collects multiple data points, averages the results, and transmits the values in the appropriate units.

To effectively monitor and regulate the environmental and nutrient parameters throughout the greenhouse and hydroponic system, a feedback loop is implemented to continuously assess the data. This feedback loop interacts with the sensor subsystem and actuator system to collect real-time data and, if necessary, take corrective action. The feedback loop is developed in C++ for the Arduino IDE, utilizing libraries designed for these sensors. Since these sensors do not have built-in serial communication, digital pin connections are used. The use of Arduino allows for highly modular and object-oriented code for easy debugging and future enhancements.

The Arduino board, equipped with several pin connections, serves as the controller for this program. The feedback loop begins by initializing all connected components, including the environmental and nutrient sensors and actuators. After a successful setup sequence, the loop continuously samples data from the sensors, averaging the measurements to determine the current environmental and nutrient parameters. If the measured levels fall below the desired thresholds, the actuator system is signaled via the Arduino GPIO pins to take corrective action.

For temperature and humidity control, the actuators used are the cooling fan and ventilation system. For the hydroponic system, the actuators include the nutrient pump and the pH Up pump. This iterative approach ensures that the system maintains its target while minimizing the risk of over- or under-saturation, rather than making sudden large corrections. The system effectively creates a stable and optimal environment for plant growth in the greenhouse.

2.5. Arduino IDE code

The model inputs relevant environmental quality parameters, such as pH, temperature, humidity, TDS (Total Dissolved Solids), and melon biomass data into the model to make predictions.

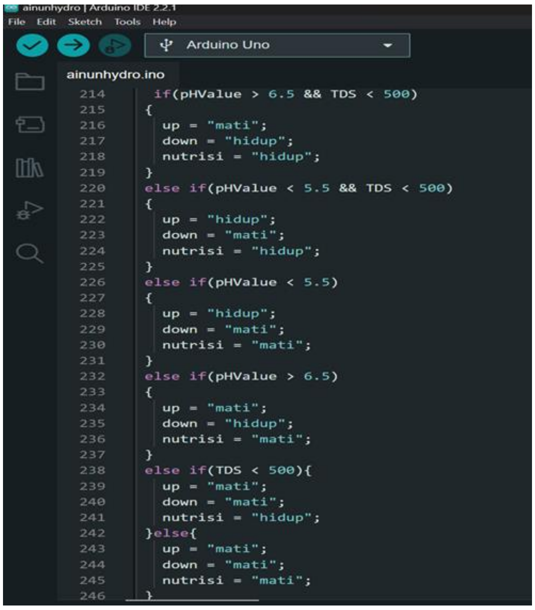

Fig. 3. Snippet of Arduino IDE code

The Arduino IDE equipped with the trained model was implemented in a greenhouse and hydroponic system. Real-time monitoring ensured that the model predictions were in line with the desired environmental quality control objectives. This integrated approach combines sophisticated Genetic Algorithm modeling with an Arduino-based environmental quality monitoring and control system, optimizing melon yields in a greenhouse environment.

3. Result and Discussion

3.1. Greenhouse Monitoring and Control System Prototype

To implement an Internet of Things (IoT) system for the purpose of monitoring and regulating the environment in a greenhouse and hydroponic system, the complete system was divided into three fundamental elements: (a) an actuator system; (b) a feedback loop; and (c) a sensor subsystem. The sensor subsystem consists of a variety of custom-designed environmental quality sensors, including those measuring temperature, humidity, TDS (Total Dissolved Solids), and pH. The information is then conveyed to an Arduino controller. The hardware setup for managing environmental quality is shown in Figure 4.

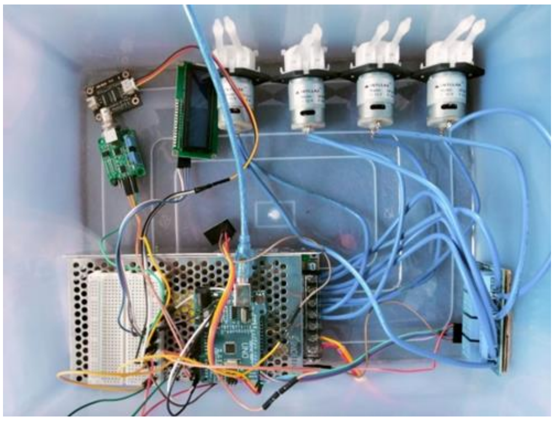

Fig. 4. Prototype of Green House monitoring and control system

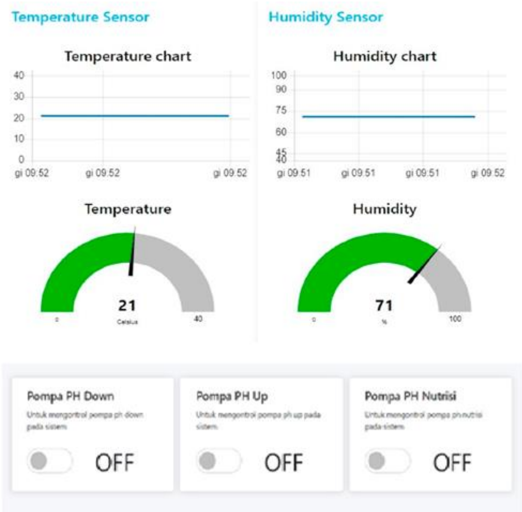

Fig. 5. Web Interface

3.2. Experimental IoT System Testing

An intelligent control system based on Fuzzy Mamdani has been implemented in a smart greenhouse to optimize melon growth in the NFT hydroponic system. The system controls environmental parameters automatically based on sensor data captured at five different times each day: 07:00, 12:00, 17:00, and 22:00.

Greenhouse Conditions at Different Times

In the morning (07:00), the temperature in the greenhouse ranges from 24-25°C with relative humidity around 70-75%. The nutrient controller works to ensure TDS (Total Dissolved Solids) is at the optimal level, namely 1050-1100 ppm, and pH is maintained in the range of 5.8-6.2.

During the day (12:00), the temperature increases significantly to 27-28°C, while humidity decreases to 60-65%. To maintain optimal conditions, the ventilation system is activated to regulate temperature, and the irrigation system is running to maintain humidity. The nutrient control system monitors and adjusts TDS to the 1100-1200 ppm range, while maintaining pH at 5.8-6.2.

In the afternoon (17:00), environmental conditions are similar to those during the day. The temperature is at 28-29°C, the relative humidity decreases to 55-60%. Ventilation and fans and irrigation systems are still active to maintain optimal environmental conditions. The nutrient controller continuously operates to ensure TDS remains at 1100-1200 ppm, and pH is maintained at 5.8-6.2.

At night (22:00), the temperature starts to decrease to 26-27°C and humidity increases to 65-70%. The ventilation system is reduced in activity, while the irrigation system continues to run to maintain humidity, and the nutrient controller adjusts the TDS to 1050-1150 ppm, with the pH remaining in the 5.8-6.2 range.

At midnight (02:00), the temperature and humidity stabilized at 24-25°C and 70-75% respectively. The irrigation system and nutrient control continue to function to maintain optimal conditions, with TDS in the range of 1050-1100 ppm, and pH maintained at 5.8-6.2.

Actuator Activation Based on Fuzzy Mamdani System

The Fuzzy Mamdani control system activates actuators based on environmental conditions detected by sensors. If the temperature exceeds 27°C, the ventilation and air conditioning system is activated to lower the temperature. If humidity falls below 60%, the irrigation system is activated to increase humidity. If the TDS is outside the 1050-1260 ppm range, the nutrient control system is activated to adjust the nutrient concentration. Additionally, if the pH falls outside the 5.8-6.2 range, the pH controller is activated to add acid or base as needed.

3.3 Data Obtained from Testing

Tests were carried out to compare the effectiveness of the Fuzzy Mamdani control system with the manual on/off control system in maintaining the stability of environmental parameters and energy consumption. Data was taken for one month with measurements at certain times every day. The following are some measurement data obtained:

Temperature

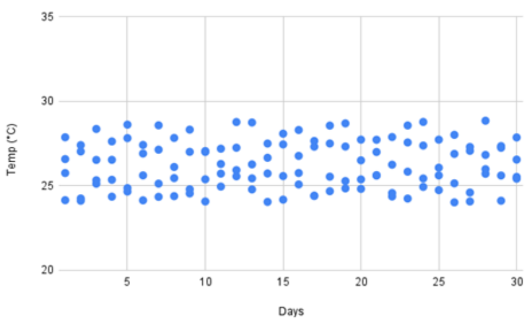

Fig. 6. Temperature data for Mamdani Fuzzy Control System

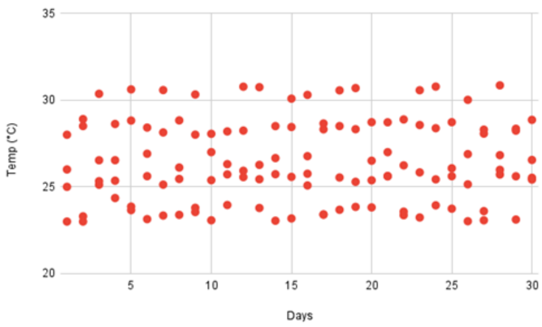

Fig. 7. Temperature data for ON/OFF Control System

Temperature data in a greenhouse controlled using a fuzzy system shows better stability compared to a manual on/off system. In the fuzzy system, the average temperature ranges from 24.05°C to 28.9°C with small daily variations, indicating a more consistent and regular arrangement. In contrast, in the manual on/off system, the average temperature ranged from 23°C to 30.9°C, with larger fluctuations and extreme values occurring more frequently. This indicates that the manual on/off system is less able to maintain the temperature within a narrow and stable range, causing more extreme changes. Overall, the data shows that the fuzzy system is more effective in regulating temperature in the greenhouse, creating a more optimal environment for plant growth.

Humidity

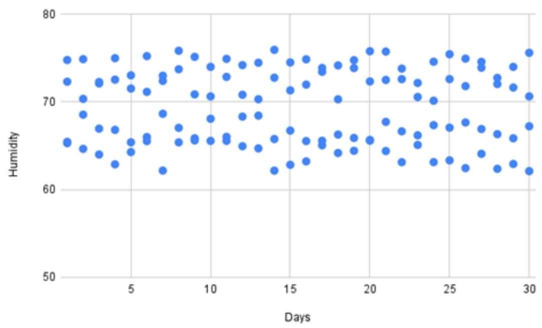

Fig. 8. Humidity data for Mamdani Fuzzy Control System

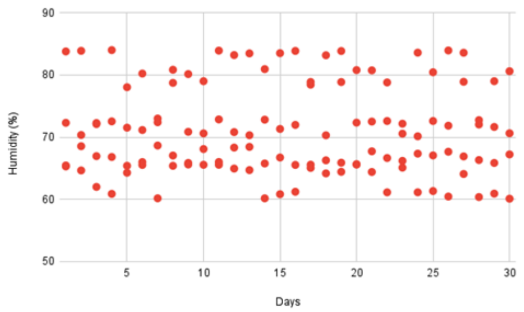

Fig. 9. Humidity data for ON/OFF Control System

Humidity data in greenhouses controlled using a fuzzy system and a manual on/off system show significant differences in humidity stability and variation. In the fuzzy system, humidity ranges from 62.11% to 75.82%, with more consistent daily values and smaller fluctuations, indicating more regular and stable control. In contrast, in the manual on/off system, humidity ranged from 60.11% to 83.98%, with larger fluctuations and extreme values occurring more frequently. In some cases, the humidity in the manual on/off system reached very high numbers, such as 83.98% on the 4th day. This indicates that manual on/off systems are less able to maintain humidity within a narrow and stable range, causing larger variations and more extreme changes. Overall, the data shows that the fuzzy system is more effective in regulating humidity in the greenhouse, creating a more optimal environment for plant growth.

TDS

Comparison between fuzzy system and manual on/off system in controlling TDS (Total Dissolved Solids) shows some important differences. In fuzzy system, TDS value varies between 1000.15 ppm to 1149.10 ppm, with an average of about 1072.76 ppm. Meanwhile, in manual on/off system, TDS value varies between 1000.15 ppm to 1149.10 ppm, with a slightly higher average of about 1081.16 ppm. Fuzzy system tends to provide more consistent control of TDS with less cooling compared to manual on/off system, which shows greater variation and less stability. This shows that fuzzy system is more effective in maintaining optimal TDS level for plant growth compared to manual on/off system.

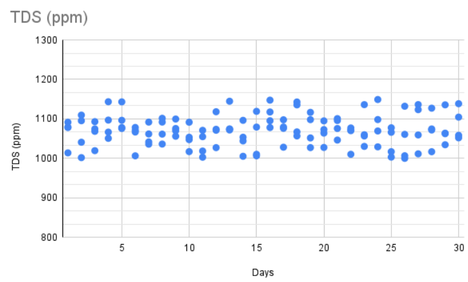

Fig. 10. TDS data for Mamdani Fuzzy Control System

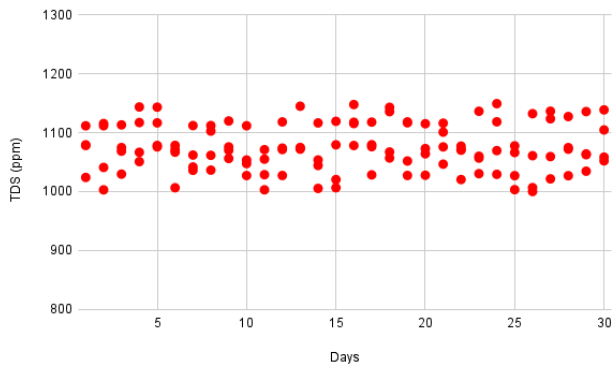

Fig. 11. TDS data for ON/OFF Control System

pH

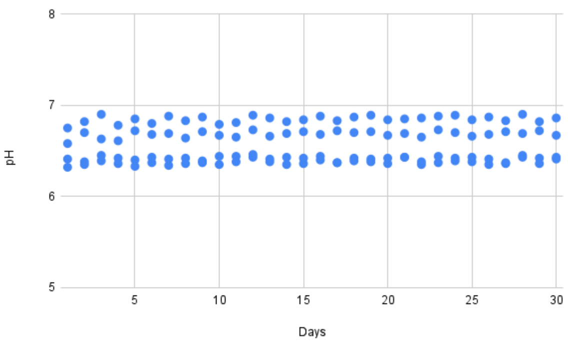

Fig. 12. pH data for Mamdani Fuzzy Control System

The comparison between the manual on/off system and the fuzzy system shows that the fuzzy system has a more stable humidity control. In the manual on/off system, the humidity ranges from 60.11% to 83.98% with an average of 70.03%, indicating significant fluctuations.

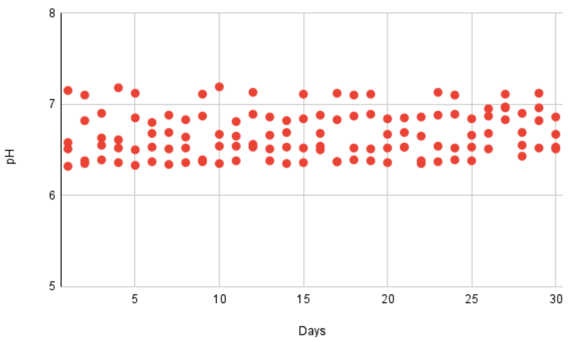

Fig. 13. pH data for On/Off System

In contrast, the fuzzy system maintains the humidity in the range of 62.11% to 75.82% with an average of 69.07%, resulting in more consistent and regular control. This shows that the fuzzy system is more effective in maintaining optimal humidity conditions compared to the manual on/off system.

Melon Growth Performance

When melon growth was analyzed over a month, the fuzzy control system outperformed the on/off system with notable benefits. Melons grown with the on/off system only reached 218 cm in height, while melons grown with the fuzzy system reached a maximum height of 250 cm in 30 days. In the fuzzy system, weekly increases were more consistent and daily growth was consistently higher.

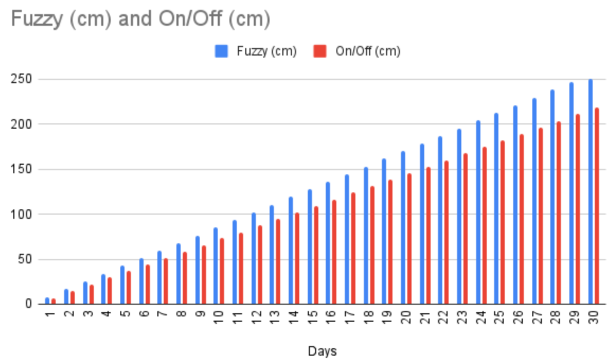

Fig. 12 Melon Growth Performance

Melons in the fuzzy system reached 59.5 cm at the end of the first week, compared to 51 cm in the on/off system; in the second week, they reached 119 cm, versus 102 cm; in the third week, they reached 178.5 cm, versus 153 cm; and in the fourth week, they reached 250 cm, versus 218 cm. The fuzzy system demonstrated significant promise in raising crop quality and productivity in contemporary agricultural applications by better adjusting environmental conditions for melon growth.

3.4 Parameter Stability and Energy Consumption Analysis

Parameter Stability

- Temperature and Humidity: The Mamdani Fuzzy System successfully maintains a more stable temperature and humidity compared to the manual on/off system. The temperature and humidity variations in the manual on/off system tend to be greater, with temperatures often exceeding 30°C during the day.
- Nutrients (TDS) and pH: The Fuzzy Mamdani system was more effective in maintaining TDS and pH within the optimal range. Manual on/off systems tended to experience greater fluctuations in TDS and pH values.

Energy Consumption

- Ventilation and Cooling: The Fuzzy Mamdani system used ventilation and cooling actuators more efficiently, only activating them when needed, while manual on/off systems tended to activate actuators more frequently to accommodate larger parameter changes.
- Irrigation: The Fuzzy Mamdani system regulated irrigation based on moisture and nutrient needs more precisely, reducing water and energy consumption compared to manual on/off systems that were more reactive to changes.

Overall, the Mamdani Fuzzy control system showed better performance in maintaining environmental parameter stability and reducing energy consumption compared to the manual on/off control system. Compared to conventional methods using manual control, the Mamdani Fuzzy system showed significant improvements in efficiency and consistency. Manual control is often unable to respond quickly to environmental changes, which can cause stress to plants. The Mamdani Fuzzy system, with its ability to respond in real-time, ensures that plants are always in optimal conditions, increasing productivity and crop quality.

3.5 Discussion

The results showed that the intelligent control system based on Fuzzy Mamdani is effective in regulating the melon growth environment in the NFT hydroponic system in a smart greenhouse. Temperature, humidity, pH, and nutrient concentration (TDS) were successfully maintained within the optimal range during one month of testing.

The control system based on Fuzzy Mamdani showed high effectiveness in regulating environmental parameters. Compared to manual control, this system offers several advantages:

- Real-Time Response: The Fuzzy Mamdani system can respond to changes in environmental conditions in real-time, which is very important in maintaining optimal conditions for plant growth.
- Precision and Consistency: This system ensures that environmental parameters are maintained within a very specific range, increasing the consistency of optimal growing conditions.
- Resource Efficiency: The automated control system reduces water and energy usage, as actuators are only activated when needed. This increases efficiency and reduces operational costs.
- Increased Productivity and Quality: By maintaining optimal environmental conditions, this system increases productivity and quality of the harvest. Melon plants grow healthier and the harvest is more uniform.

The findings of this study have several important implications:

- Agricultural Technology Development: This study demonstrates the great potential of intelligent control technology in improving efficiency and yields in modern agriculture. This can encourage further development of smart greenhouse technology and automated control systems.
- Sustainability Improvement: By reducing water and energy usage, this system contributes to more sustainable agricultural practices. This is especially important in the era of climate change and resource constraints.

4. Conclusion and Future Research

4.1. Conclusion

The research effectively created and applied the Fuzzy Mamdani-based intelligent control system to manage the melon growth conditions in the NFT hydroponic system within the smart greenhouse. By maintaining temperature, humidity, nutrient concentration (TDS), and pH within the appropriate range with minimal variations, plants can experience ideal growth circumstances.

Furthermore, the Fuzzy Mamdani system demonstrated superior efficiency in resource utilization. cooling fan and ventilation, and irrigation are meticulously controlled and activated only when necessary, resulting in a substantial reduction in energy and water usage. This enhanced efficiency not only diminishes operational expenses but also promotes the use of more environmentally-friendly agriculture methods.

The utilization of this technology led to a substantial enhancement in both the efficiency and caliber of the melon harvest. Plants regulated by the Fuzzy Mamdani system exhibited enhanced and consistent growth, characterized by increased plant height, leaf count, and fruit weight, as well as superior quality, in comparison to plants regulated by a manual system.

4.2. Future Research

The research proposes several recommendations for future development, which include enhancing control algorithms, incorporating IoT technologies for monitoring and remote control, implementing the systems in various crop types, and conducting economic and sustainability analyses. This research adopts a sustainable improvement approach and emphasizes the utilization of sophisticated technology. It serves as a crucial basis for the future development of farming technologies that are more efficient, productive, and sustainable.

Acknowledgment

We would like to express our gratitude to our funding organizations, Ministry of Education, Culture, Research and Technology of Indonesia, for their invaluable support and contributions to this research project. This work was made possible by the combined efforts and support of these individuals and institutions.

Author contributions

Rizal Tjut Adek: Conceptualization, Methodology, Software, Field study **Munirul Ula:** Data curation, Writing-Original draft preparation, Software, Validation., Field study **Bustami:** Visualization, Investigation. Emmia Tambarta Kembaren: Writing-Reviewing and Editing

Conflicts of interest

The authors declare no conflicts of interest.

References

[1] Smith, J. (2020). Modern Agricultural Challenges. Journal of Agricultural Science, 45(2), 123-135.

[2] Johnson, A., & Brown, B. (2019). Hydroponic Systems: A Comprehensive Review. Advances in Plant Science, 12(3), 234-248.

[3] Garcia, C., et al. (2021). Benefits and Challenges of Hydroponic Farming. Sustainable Agriculture Research, 8(4), 567-580.

[4] Lee, K. (2018). Environmental Factors Affecting Plant Growth in Controlled Environments. Horticultural Science, 30(1), 45-58.

[5] Wang, Y., & Liu, Z. (2022). Smart Greenhouse Technologies: A Review. Journal of Agricultural Engineering, 55(3), 321-335.

[6] Patel, H., et al. (2020). Sensor Technologies for Precision Agriculture. IEEE Sensors Journal, 20(10), 5107-5120.

[7] Anderson, R. (2021). Efficiency and Productivity in Smart Greenhouses. Agricultural Systems, 190, 103093.

[8] Thompson, E. (2019). Resource Management in Smart Agriculture. Renewable Agriculture and Food Systems, 34(4), 362-375.

[9] UN FAO. (2023). The State of Food and Agriculture: Water Scarcity and Energy Challenges. Rome: Food and Agriculture Organization of the United Nations.

[10] Zadeh, L. A. (1965). Fuzzy Sets. Information and Control, 8(3), 338-353.

[11] Mamdani, E. H., & Assilian, S. (1975). An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller. International Journal of Man-Machine Studies, 7(1), 1-13.

[12] Ross, T. J. (2017). Fuzzy Logic with Engineering Applications. John Wiley & Sons.

[13] Chen, G., & Pham, T. T. (2000). Introduction to Fuzzy Sets, Fuzzy Logic, and Fuzzy Control Systems. CRC Press.

[14] Kumar, A., et al. (2023). Smart Greenhouse Control Using Fuzzy Logic: A Case Study on Melon Cultivation. Journal of Intelligent Systems in Agriculture, 15(2), 178-192.

[15] Jones, H. G. (2013). Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. Cambridge University Press.

[16] H. Jaiswal, K. R. P, R. Singuluri, and S. A. Sampson, IoT and Machine Learning based approach for Fully Automated Greenhouse, in 2019 IEEE Bombay Section Signature Conference (IBSSC), Oct. 2019. doi: 10.1109/ibssc47189.2019.8973086.

[17] M. A. A. Ahmed and S. M. Reddy, “Smart Hydroponic System and Monitoring of Plants Health through Machine Learning,” Int J Res Appl Sci Eng Technol, vol. 11, no. 6, pp. 4261–4263, Jun. 2023.

[18] U. Arora, S. Shetty, R. Shah, and D. K. Sinha, “Automated Dosing System in Hydroponics with Machine Learning,” in 2021 International Conference on Communication information and Computing Technology (ICCICT), Jun. 2021.

[19] Lopes, R. V., et al. (2021). IoT in Precision Agriculture: A Systematic Literature Review. IEEE Internet of Things Journal, 8(18), 14227-14247.

[20] Castañeda-Miranda, A., et al. (2020). Fuzzy Greenhouse Climate Control System Based on a Field Programmable Gate Array. Biosystems Engineering, 194, 135-150.

[21] M. Lavanaya and R. Parameswari, “Soil Nutrients Monitoring For Greenhouse Yield Enhancement Using Ph Value with Iot and Wireless Sensor Network,” in 2018 Second International Conference on Green Computing and Internet of Things (ICGCIoT), Oct. 2018. doi: 10.1109/icgciot.2018.8753083.

[22] Ödük, M. N., & Allahverdi, N. (2019). The Advantages of Fuzzy Control Over Traditional Control System in Greenhouse Automation. 2019 1st International Informatics and Software Engineering Conference (UBMYK), 1-4.