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Autonomous Nutrient Controller System for Hydroponic Honey Melon Based on the Integration of Artificial Intelligence Algorithms According to Planting Time

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***Abstract*—The honeydew melon cultivation model using the hydroponic greenhouse method has been widely applied due to its ease in controlling nutrients and the environment. However, complaints from farmers regarding the inaccuracy of nutrient levels and the dynamic environmental changes, that hinder plant growth and fruit quality, have surfaced. The development of autonomous control technology is crucial as a strategic solution to this issue since the quality of honeydew melon management lies in achieving precise and accurate nutrient levels. On the other hand, managing standardized nutrient composition often becomes a challenge for farmers as the needs constantly change over time. Conventional systems are not yet capable of accurately measuring nutrient levels in line with the plant's growth stages. According to the objectives of this study, which is to improve the productivity and quality of honeydew melons based on the increase in the sweetness index, the development of an autonomous nutrient control system is proposed. This system integrates artificial intelligence algorithms, namely CNN and Fuzzy Logic, to process plant height image data and multisensor data for system control processes. The research findings that applying this integrated technique has resulted in a sweetness increase of 11.7%, or from the previous value of 15 brix to 17 brix. Even a one-point increase in the brix value leads to a sugar increase of 1 gram per 100 gram of liquid content in the fruit, contributing significantly to the market value. These results indicate that AI-supported agricultural management can be realized in future modern farming practices.**

***Keywords*—Artificial Intelligence; Convolutional Neural Network (CNN); Fuzzy Logic; Hydroponic; Nutrient Controlling.**

I. INTRODUCTION

Culturing honeydew melons using hydroponics has become an increasingly popular method in modern agriculture. Hydroponics offers various advantages, including efficient water usage, better environmental control, and increased crop yields [1]-[4]. However, a significant challenge in hydroponic systems is managing nutrient delivery precisely to support optimal plant growth and high fruit quality. However, in reality, the dynamic environmental changes that are difficult to control have worsened nutrient delivery to the plants, as the systems developed so far are still conventional and semi-automatic, lacking the ability to adaptively respond to the changing environment [5]-[10]. Therefore, it is necessary to develop an autonomous nutrient management system for this type of plant to address the weaknesses of the previous system, allowing the issues that have arisen to be resolved.

As is known, several indicators for measuring and testing the quality of premium melon varieties include sweetness level, the appearance of the fruit's outer skin, and the size of the fruit [11]-[15]. Improving the efficiency and effectiveness of managing these premium varieties is not easy and cannot solely rely on existing systems. One of the innovations that can be proposed is involving artificial intelligence technology to enhance honeydew melon cultivation management, particularly to improve the irrigation control system. This aligns with the aim of this research, which is to develop a smart farming management system specifically for hydroponic greenhouse honeydew melon cultivation. The differentiation of the system being developed refers to the optimization of nutrient control through the integration of artificial intelligence algorithms, namely Convolutional Neural Network (CNN) and Fuzzy Logic, to create an autonomous system. The process begins with image data processing of the honeydew melon plant height by the CNN algorithm, whose results are integrated with environmental data from multisensors to be used as input datasets for fuzzy logic algorithm in autonomously controlling the system.

This research demonstrates that artificial intelligence algorithms have great potential in addressing various challenges in modern agriculture compared to previous studies. In studies [16]-[21], fuzzy intelligence algorithms were applied to develop an automatic irrigation management system for indoor plant cultivation. Still, they did not discuss the testing and measuring environmental changes around the growing medium. Similar approaches were taken in studies [22]-[26], which focused more on applying fuzzy intelligence algorithms to respond to and measure climate changes affecting plant growth, yet concentrated primarily on nutrient testing. In general, several artificial intelligence algorithms have been introduced in previous research, but the concept of collaborating and integrating multiple AI algorithms has not been fully implemented. Therefore, this integration represents a novel development in this research.

The proposed development of autonomous nutrient control based on the integration of artificial intelligence should be able to address the weaknesses in agricultural management, particularly in irrigation and nutrient management. Therefore, the results of this research development can contribute to the optimization of modern agricultural management, specifically in improving productivity and product quality, ultimately leading to higher market value and significant profits. This is well aligned with the ultimate objectives of this research.

II. RELATED WORK

Research by [27]-[30] has shown that the implementation of intelligent systems in hydroponic nutrient control can significantly improve nutrient use efficiency and crop yields. They found that intelligent systems can reduce nutrient consumption by up to 20% while increasing crop yields by 15% compared to conventional methods. These systems use machine learning algorithms to predict plant nutrient needs based on historical data and current environmental conditions, demonstrating that AI can optimize nutrient delivery with high precision. This aligns with the findings of studies [31]-[35] that developed machine learning algorithms to predict plant nutrient needs with high accuracy. Their algorithms use datasets that include various plant growth parameters and environmental conditions, allowing for more precise and efficient nutrient management. Although much research has been conducted on the use of artificial intelligence in various hydroponic plant cultivation systems, studies specifically investigating the integration of AI algorithms for nutrient control are still limited and fragmented in their implementation. Therefore, this study aims to fill this gap by developing an autonomous nutrient control system based on image data of plant height growth and fruit sweetness levels in honeydew melons. According to [36][37], the use of artificial intelligence to optimize nutrient delivery can significantly improve the quality of melon crop yields by leveraging plant growth data at various stages of the growth cycle, which impacts the measurement results of increased fruit sweetness levels.

III. METHOD

This research develops a design for an autonomous nutrient control system built on artificial intelligence to be applied to hydroponic honeydew melon plants. The system integrates the operation of a Convolutional Neural Network (CNN) algorithm, which processes image data of plant height growth at intervals throughout the planting period, with a fuzzy logic algorithm that focuses on autonomously controlling the nutrient control system [38]-[42]. The methodological approach uses a design method to develop, implement, and test the integration of the developed artificial intelligence algorithms as shown in the flowchart in Fig. 1.

This integration concept explains how to combine image processing data with data from other sensors, forming a dataset that utilized by the fuzzy algorithm to control the system. The first process is performed by the CNN algorithm, which processes the plant height image into a series of classified binary data, and then the results are combined with other sensor data. The combined image data and sensor data are processed by the fuzzy algorithm to initiate and establish autonomous nutrient control rules. Meanwhile, the CNN algorithm collects image data performs preprocessing for image data analysis, and extracts key features related to plant growth. The image processing initially involves a convolution function by multiplying the image matrix with a filter (kernel) to produce a feature map, where the convolution operation can be calculated using equation (1) [43].

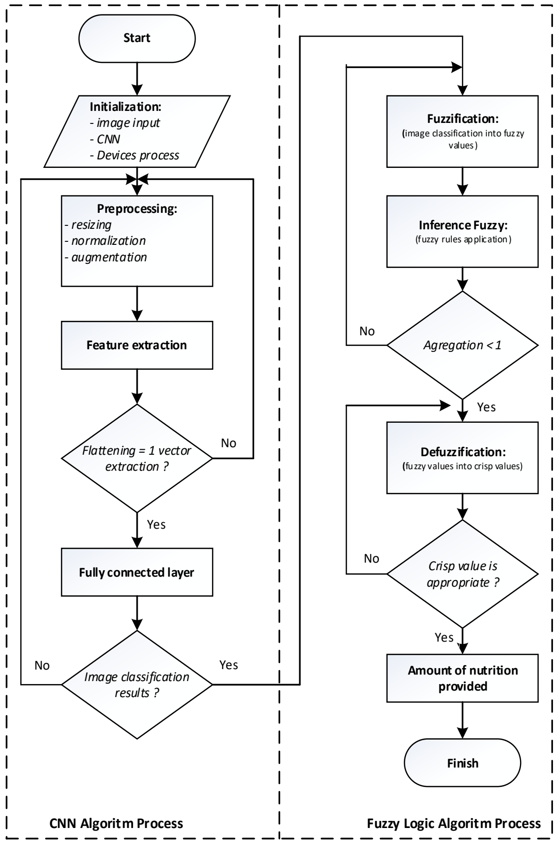


Fig. 1. Flowchart diagram of the CNN-LF algorithm integration for autonomous honey melon nutrient control

$$(f * k)(i,j) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f(m,n).\, k(i-m, j-n) \quad (1)$$

where the parameter f represents the plant height image that will be convolved with the filter kernel k to reduce the size of the feature map during pooling, which can be measured by equation (2)[43].

$$y_{i,j} = max(x_{i+k,j+l}) \quad (2)$$

In the final stage, the integration or combination of all the features extracted from the plant height image dataset into the CNN output for classification tasks can be quantified using equation (3)[43]-[44].

$$y = Wx + b \quad (3)$$

To convert the classification results of high-resolution plant image features into fuzzy membership functions, the weighting values (W) need to be optimized from the input images (x) that have undergone kernel filter extraction. Before these image features are converted into fuzzy input values categorized as "low", "medium", and "high" memberships, normalization to a specific range typically between 0 and 1 is necessary to ensure consistency. This normalization can be measured using equation (4)[45].

$$f_{norm} = \frac{f - f_{min}}{f_{mak} - f_{min}} \tag{4}$$

After defining the fuzzy membership functions, the fuzzy rules (fuzzy inference) can be applied using "if-then" rules that combine the fuzzy values of the extracted tall plant features. The rules used in the study are described as follows:

Rule1: If plant height is Medium and sweetness level is High, then nutrient supply is Low.

Rule2: If plant height is High and sweetness level is Low, then nutrient supply is High.

Rule3: If plant height is Short and sweetness level is Medium, then nutrient supply is Medium.

These rules were derived from the extension of fuzzy inference equations using a minimum approach (using the AND operator) as per equation (5)[46]-[48].

$$\mu c(y) = min\ \{\mu A(x_1), \mu B(x_2)\} \tag{5}$$

where x_1 represents the plant height feature and x_2 denotes the nutrient level provided to the plant. The fuzzy output values are converted into a crisp value y^* to control the autonomous nutrient control system through the application of the following defuzzification equation (6)[46]-[48].

$$y^* = \frac{\int y.\mu c(y)dy}{\int \mu c(y)dy} \tag{6}$$

The value y^* obtained from the defuzzification process will be used as the final decision for autonomous nutrient control. Meanwhile, the value y represents the amount of nutrients provided to the plants, adjusted according to the classification of image features extracted by the CNN.

IV. Design of System and Algorithm Integration Models

A. *Architecture of the Autonomous Nutrient Control System*

The system design is built with several key elements, including detection sensors such as a camera, humidity sensor, temperature sensor, and RTC (Real-Time Clock). The camera sensor output generates plant object images processed by the CNN algorithm, while the outputs of the other sensors are handled by the fuzzy logic algorithm [49]-[54]. The integration process of the algorithms is carried out by a microcontroller (mini-PC), which will subsequently regulate the nutrient levels of the plants. The architecture of this control system design is depicted as shown in Fig. 2.

Based on Fig. 2, the camera sensor visually detects changes in the height of the melon, where the resulting data is then extracted into features in the form of a series of binary data. This binary image data, along with sensor data, is processed by the fuzzy algorithm on a mini PC to obtain a fuzzy control rule model for the autonomous system. The fuzzy rules are applied to autonomously operate the irrigation system, including distributing liquid nutrients to each plant [55]-[61].

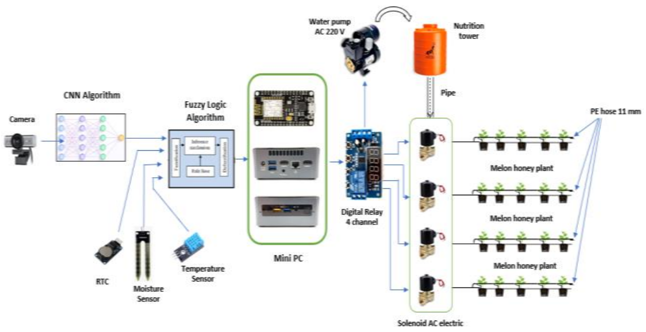


Fig. 2. Block diagram of autonomous nutrient system design

B. *Process of integrating artificial intelligence algorithms*

The stages of integrating artificial intelligence algorithms begin with the feature extraction process from images by the CNN algorithm. The results of this image feature extraction are then processed through fuzzification by the fuzzy logic algorithm to obtain a control scheme for the autonomous nutrient control system. The image processing stage up to the classification value generated by the CNN algorithm is illustrated in Fig. 3.

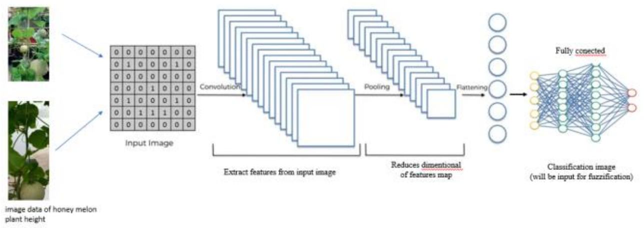


Fig. 3. Stages of plant object processing in a CNN algorithm

In the convolution process, the input image is represented in three dimensions: height (h), width (w), and depth (d), or expressed as a 3D tensor $f_h \times f_w \times d$. This dimensional scale is then filtered (kernel) to obtain the feature map $[Y(I,j)]$ using the developed equation (1).

$$Y(i,j) = (f * k)(i,j) = \sum_{m=0}^{f_h-1} \sum_{n=0}^{f_w-1} \sum_{d=0}^{d-1} f(i + m, j + n, d)\ .\ k(m.n, d) \tag{7}$$

The feature maps resulting from convolution need to be activated using the ReLU function [62]-[65] so that the CNN can model and learn from more complex data.

$$ReLU\ (x) = max\ (0, x) \tag{8}$$

To obtain image feature classification to be used in the fuzzification process, these feature maps need to be down sampled from their pixel size using a maximum pooling approach.

$$Y_{pool}(i,j) = \max\ [Y(m,n)| \in [i.p, (i+1).p - 1], n\ \in [j.p, (j+1).p - 1]\} \tag{9}$$

The results of image data processing by CNN algorithms consist of classifying the height of honeydew melon plants into three categories: short, medium, and tall, according to predefined scale ranges as illustrated below [66]-[70].

$$Inage\ of\ plant\ height\ (X) = \begin{cases} Short: if\ 0 \leq a \\ Moderate: if\ a \leq X \leq b \\ Height: if\ b > X \end{cases}$$

For the classification results of image data during *short:* $0 \leq a$ represents the conditions of nutrient quantity and concentration provided to plants within the time interval of 0 days to 14 days. Meanwhile during *moderate:* $a < X \leq b$ represents nutrient provision within the interval of 15 days to 30 days. At *height:* $b > X$ represents nutrient provision conditions from over 30 days until nearing harvest. These divisions and categorizations will subsequently form part of the fuzzification dataset. In the fuzzy control process, the number of fuzzy data sets consists of three membership functions, namely image classification data obtained from the CNN algorithm, temperature, and soil moisture [71][72]. The fuzzy control system modelling in this research is illustrated as shown in Fig. 4.

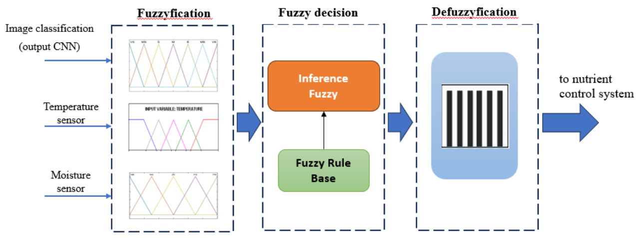


Fig. 4. Architecture of logic fuzzy algorithm to nutrient control system

Fuzzy rules that combine the input variables of plant height classification images, temperature, and humidity to determine the amount of nutrients based on the implementation of Fig. 4 can model the fuzzy rules as follows:

Rule1: IF plant height is short AND temperature is low AND humidity is low THEN nutrition is low

Rule2: IF plant height is short AND temperature is low AND humidity is medium THEN nutrition is low

Rule3: IF plant height is short AND temperature is low AND humidity is high THEN nutrition is medium

Rule4: IF plant height is short AND temperature is medium AND humidity is low THEN nutrition is low

Rule5: IF plant height is short AND temperature is medium AND humidity is medium THEN nutrition is medium

Rule6: IF plant height is short AND temperature is medium AND humidity is high THEN nutrition is medium

Rule7: IF plant height is short AND temperature is high AND humidity is low THEN nutrition is medium

Rule8: IF plant height is short AND temperature is high AND humidity is medium THEN nutrition is medium

Rule9: IF plant height is short AND temperature is high AND humidity is high THEN nutrition is high

Rule10: IF plant height is medium AND temperature is low AND humidity is low THEN nutrition is medium

Rule11: IF plant height is medium AND temperature is low AND humidity is medium THEN nutrition is medium

Rule12: IF plant height is medium AND temperature is low AND humidity is high THEN nutrition is high

Rule13: IF plant height is medium AND temperature is medium AND humidity is low THEN nutrition is medium

Rule14: IF plant height is medium AND temperature is medium AND humidity is medium THEN nutrition is medium

Rule15: IF plant height is medium AND temperature is medium AND humidity is high THEN nutrition is high

Rule16: IF plant height is medium AND temperature is high AND humidity is low THEN nutrition is high

Rule17: IF plant height is medium AND temperature is high AND humidity is medium THEN nutrition is high

Rule18: IF plant height is medium AND temperature is high AND humidity is high THEN nutrition is high

Rule19: IF plant height is high AND temperature is low AND humidity is low THEN nutrition is medium

Rule20: IF plant height is high AND temperature is low AND humidity is medium THEN nutrition is high

Rule21: IF plant height is high AND temperature is low AND humidity is high THEN nutrition is high

Rule22: IF plant height is high AND temperature is medium AND humidity is low THEN nutrition is medium

Rule23: IF plant height is high AND temperature is medium AND humidity is medium THEN nutrition is high

Rule24: IF plant height is high AND temperature is medium AND humidity is high THEN nutrition is high

Rule25: IF plant height is high AND temperature is high AND humidity is low THEN nutrition is high

Rule26: IF plant height is high AND temperature is high AND humidity is medium THEN nutrition is high

Rule27: IF plant height is high AND temperature is high AND humidity is high THEN nutrition is high

This fuzzy rule determines the appropriate output, which is the amount of nutrition that should be given to the honey melon plant. The implementation of this rule will enable better autonomous control based on the actual conditions of plant height, temperature, and humidity during the planting interval. In this study, the distribution of nutrient quantities for honeydew melon plants is divided into 5 clusters corresponding to each growth period [73]-[75], as shown in Table I.

TABLE I. NUTRIENT DELEVERY SCENARIOS

Plant age (days)	The amount of nutrient supply per day (times)	Nutrient volume per day (ml)
0 – 7	6x	600
8 – 14	7x	700
15 – 21	8x	900
22 – 36	9x	1100
>37	10x	1200

V. Result And Discussion

This test was conducted to measure the performance of the developed system in improving the method of nutrient delivery to honeydew melon plants, which was previously done conventionally [76]. The working principle of the autonomous system in this study is designed to produce an accurate value for the amount of nutrients provided over a specific time interval, aiming to enhance the quality of the melons based on the sweetness level indicator. The testing of the CNN algorithm begins with detecting the plant height image using a camera sensor, resulting in image labels in the form of plant height scales: short, medium, and height, as shown in Fig. 5.

Fig. 5. Input image of honey melon plant height for each planting period

The interface design of the fuzzy logic system to regulate the nutrient control device, which will operate autonomously is shown in Fig. 6.

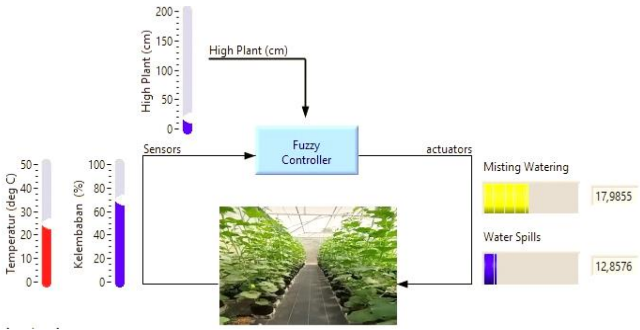


Fig. 6. The interface display of the fuzzy control system for autonomous nutrient management

The system test data was obtained from the beginning of the planting period with daily monitoring throughout the plant's growth, followed by measuring the changing temperature and humidity of the growing medium. Data collection was conducted over 60 days, aligning with the standard time interval for honeydew melon cultivation, and the final results are presented in Table II.

TABLE II. Test Result Data For System Control

Days	Image label	Plant height (cm)	Average temperature (^{0}C)	Average humidity (%)
1-16	short	0 – 50	25-29	62-73
17-35	medium	50 – 150	24-29	43-61
36-60	height	>160	21-29	18-42

It provides the volume of nutrients from the beginning of planting until just before harvest showing a reduction because it is closely related to the sweetness quality of the melon fruit. This reduction process aims to maintain and periodically increase the sweetness level of the fruit. Typically, melon cultivation usually involves gradually reducing the amount of nutrients provided to the growing medium as the harvest period approaches [77]. This decreasing trend can be more clearly seen from the test results as shown in Fig. 7.

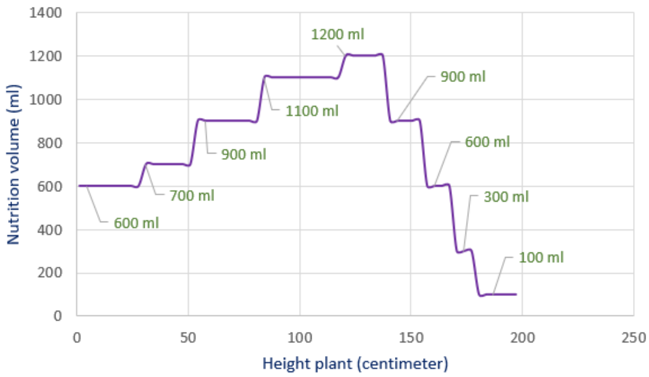
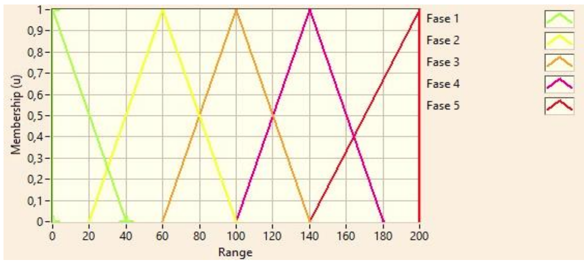


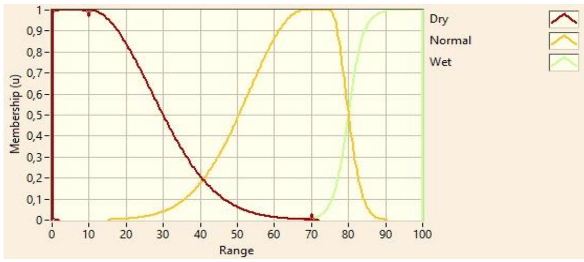
Fig. 7. Trend in providing nutrient levels in the planting period

A. *Setting the Membership Function Point of the Autonomous Nutrient Control System*

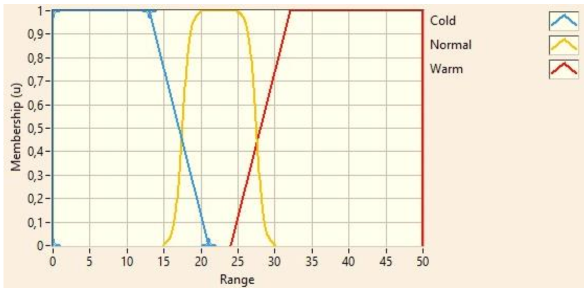
The fuzzy logic algorithm will respond and display the performance graph of the membership function for each input data variable as a representation of the autonomous system's performance during the control process. The membership function graph, as shown in Fig. 8, illustrates that each processed data variable has different control rules. This is influenced by changes in plant height and differences in nutrient needs detected by the installed sensors. The autonomous system's activity, when receiving rapid input changes, will adjust flexibly towards normal conditions, aligning with the expected outcome standards [78].



a) plant height response



b) humidity response



c) temperature response

Fig. 8. Output membership functions fuzzy logic algorithm at autonomous nutrition controlling system

B. *Results of Fruit Sweetness Level Comparison*

The sweetness level of honeydew melons was measured and tested using a comparative method [79][80], where the sweetness was assessed gradually at each growth stage, alongside testing the sweetness level by comparing the results of honeydew melons grown without an autonomous system and those grown with an autonomous system. The final results showed an increase in the sweetness level of honeydew melons when using the autonomous system compared to without it. This can be seen in the results presented in Table III.

The testing and measurement process for fruit sweetness levels was conducted over the same period between the non-autonomous system and the autonomous system to demonstrate an increase in melon sweetness levels. The results showed an 11.7% increase when the autonomous system was applied. The success indicator of this sweetness enhancement can be seen in Fig. 9, which shows a larger change in fruit sweetness value to 17 brix. Previously, the sweetness value without applying the autonomous system was 15 brix.

Fig. 9. Testing the sweetness level of honeydew melon using an autonomous system

C. *Testing the Accuracy of Autonomous Systems*

Another indicator for measuring the quality of the developed system's performance is testing the accuracy level of the system when controlling the nutrition of melon plants, based on the difference in results between testing with and without using the developed system. This difference is represented as an error percentage, which is related to the accuracy level of the system's performance. Fig. 10 shows a trend curve illustrating the comparison of the final accuracy testing results of the system, represented as a percentage error value.

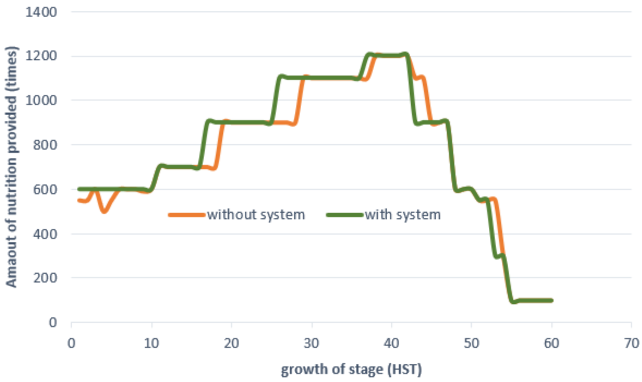


Fig. 10. Results of the comparison test of system accuracy levels

According to the trend curve results shown in Fig. 10, implementing an autonomous system for plant nutrition control has achieved an accuracy improvement in system performance of approximately ±4.91% compared to the previous system performance. Specifically, the average accuracy achievement values can be seen in Table IV. The improvement in autonomous system performance is primarily determined by the system's ability to adapt to dynamic environmental conditions [81]. This could also potentially contribute to the enhancement of the quality of honeydew melon fruit according to the recommended standards.

TABLE III. DATA OBSERVED SWEETNESS LEVELS OF HONEYDEW MELONS

Days	Image label	Measurement & testing of fruit sweetness levels (Brix)		Enhancement of fruit sweetness levels (%)	Planting Period (HST)
		Without autonomous system	With autonomous system		
1-16	short	< 10	< 10	± 0	planting stage
17-35	medium	± 13-14	± 14-16	± 12,5	mid-stage
36-60	height	±15	±17	± 11,7	harvest stage

TABLE IV. AVERAGE FINAL RESULT OF SYSTEM COMPARISON TESTING

Difference in results (%)		Average accuracy (%)		System performance improvement (%)
Without autonomous system	With autonomous system	Without autonomous system	With autonomous system	
± 6.67	± 1.76	± 93.32	± 98.23	± 4.91

VI. Conclusion

The development of an autonomous system for controlling the nutrient supply in honeydew melon cultivation through the integrated application of artificial intelligence algorithms has proven to improve nutrient management performance and successfully enhance the quality level of honeydew melons. The performance improvement indicator showed an increase of 4.91%, with an accuracy result of 98.23%, compared to the previous value of 93.32%. Meanwhile, the quality improvement indicator, measured by the increase in fruit sweetness, reached 17 Brix, up frm the previous value of 15 Brix during the cultivation period, reflecting an 11.7% increase. The successful performance of this system offers significant opportunities to contribute to the development of modern and sustainable agricultural management models in the future.

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