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Optimizing Water Level on Japanese Cucumber (*Cucumis sativus* L.) with Unpowered Automatic Fertigator Technology (FONi)

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ABSTRACT

The Japanese cucumber (Cucumis sativus L.) requires adequate and continous water supply throughout its growth period. Unpowered Automatic Fertigator (FONi) technology supplies water and nutrients based on plant water uptake without electricity. The purpose this study is to determine the optimal water level for Japanese cucumber cultivated by the FONi technologi. This study evaluated the effects of four water levels (4, 8, 12 and 16 cm) on the growth and yield of Japanese cucumber. Each level of research has 10 plant samples. Observation variables are plant length, stem diameter, number of leaves, analysis of chlorophyll, fruit weight, root length, total irrigation volume and environmental parameters. The data obtained is averaged and presented in line graph and bar graph. The results of the study with a water level of 8 cm obtained the highest results, namely plant length 231,43 cm, stem diameter 8,93 mm, number of leaves 25,5 leaves, fruit weight 394 g, root length 49,47 cm. These finding indicate that maintaining an 8 cm water level is potentially suitable for supporting Japanese cucumber growth and yield using FONi uder the tested greenhouse conditions.

1. INTRODUCTION

Water availability is one of the important factors in plant cultivation. As the main raw material in the photosynthesis process, the availability of water determines the growth and development of plants. The Japanese cucumber plant (*Cucumis sativus* L.) has a very high and consistent water requirement during the growing period. The implementation of appropriate and effective irrigation strategies can save water and increase cucumber yields (Khan *et al*., 2024). Cucumbers have been considered as fruits and can be utilized as food due to the presence of high nutritional content. Cucumber fruit generally contains carbohydrates 2.2%, lipids 0.1%, proteins 0.6% and water 95% (Javid *et al*., 2024). Severe deficits in irrigation volume and frequency induce water stress that adversely affects stomatal conductance and leaf expansion, thereby suppressing vegetative growth and reducing cucumber fruit yield (Khan *et al*., 2024).

The use of the right irrigation system can meet the water needs of plants. One of the cultivation methods with irrigation systems that is currently being developed is the hydroponic method Hydroponics has several systems, hydroponics drip irrigation system, hydroponics DFT (Deep Flow Technique) system and NFT (Nutrient Film Technique) system are the most commonly used systems in agricultural cultivation using hydroponic methods (Pribadi & Sodiq, 2023). These technological hydroponic advancements have their own challenges. The continuous operation of pumps, LED lighting, filtration units, and sensor networks substantially increases the electricity demand of a system. In other words, while IoT integration improves resource efficiency in water and nutrients, there is a concern regarding energy efficiency. This trade-off underscores the necessity of energy assessment as a critical step in evaluating the long-term sustainability of hydroponics (Serikov *et al*., 2026).

As part of efforts to streamline the use of electricity and nutrient water in plant cultivation, IPB Univeristy has developed an urban agriculture device known as the Unpowered Automatic Fertigator (FONi). The FONi system consists of pots that are connected in series using pipes, the first pot is used as a water level control. Water will flow to a lower height pot with the mechanism of the communicating vessels and capillarity (Dewi *et al*., 2020). This system utilizes the concept of evapotranspiration based irrigation to suplly plant water requirements without the use of electricity. Based on research Hedianty *et al*. (2025), FONi is able to distribute water proportionally according to the needs of plants, with a water use efficiency of 98.9%, making it an efficient strategy to optimize water use and increase land productivity in the midst of water scarcity.

The FONi system, which uses a mechanism of communicating vessels and capillarity, makes water level regulation one of the things that must be considered so that plants can grow properly. Cucumber plants are very susceptible to waterlogging because they have a shallow root system and high oxygen requirements. Anaerobic conditions accelerate root damage (Olorunwa *et al*., 2022). Experimental irrigation studies reveal that cucumbers are highly susceptible to water deficit due to their limited root distribution, with roughly 85% of the total root length localized in the top 30 cm of soil (Odhiambo & Aguyoh, 2022). The height of the water level directly affects the availability of water for plants. The availability of sufficient water is needed by plants. Excessive or insufficient watering can have a bad impact on plants. Based on research Khan *et al*. (2024), plants that lack water will result in inhibited metabolic processes in plants which has an impact on the growth and development process of a plant. Water stress that occurs in cultivated plants has an impact on the inhibition of the assimilate distribution in the reproductive organs and photosynthesis processes. Based from the description above, this study was carried ot to determine the water level that influences the growth and production of japanese cucumber plants using Unpowered Automatic Fertigator (FONi) technology. The hypothesis of this study is that the treatment of water level of 8 cm is better in the growth and yield of Japanese cucumber plants.

2. MATERIALS AND METHODS

2.1. Time and Place

This research was carried out from December 2025 to February 2026. The research takes place in the greenhouse of the Faculty of Agriculture, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya City. The research location is at an altitude of 5 meters above sea level, with an average temperature ranging from 29–33°C and an average rainfall of 201-300 mm/month with relative humidity between 60% to 81%.

2.2. Tools and Materials

The tools used in this study are water drums, plastic buckets, pvc pipes, automatic float valve, stop kran, seedling trays, hoes, scissors, sprayer tanks, measuring cups, digital scales, calipers, meters, pH meters, TDS meters, scissors, SPAD chlorophyll meters, Automatic Weather Station (AWS). The Unpowered Automatic Fertigator (FONi) design was detailed in Figure 1.

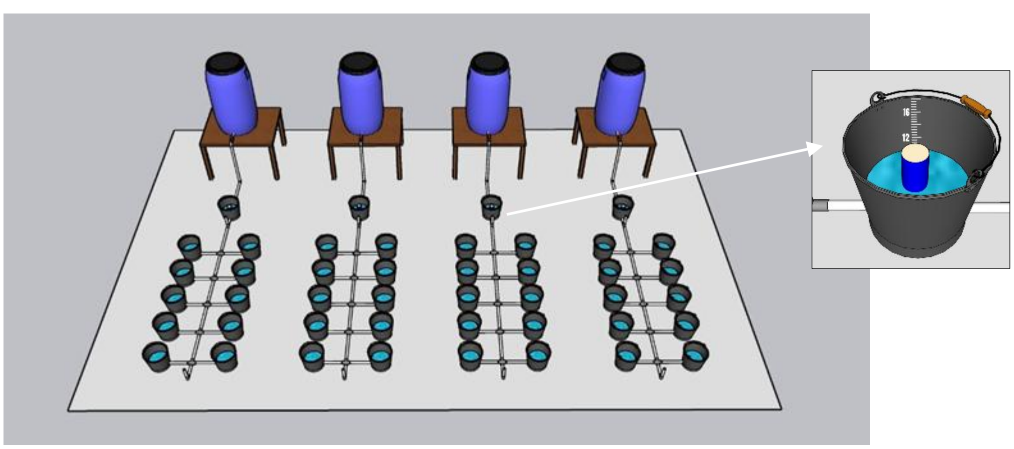

Figure 1. FONi installation design

The materials used in this study are Japanese cucumber seeds of the Ronaldo F1 variety, polybag 40 cm × 40 cm, pipe glue, seal tape, water, soil, husk charcoal, goat manure, AB Mix nutrition, warp rope, Gandasil D and B fertilizer, Curacron 500 EC insecticide, Demolish 18 EC insecticide, Antracol 70 WP fungicide,

2.3. Research Procedure

This study uses a single factor, namely the water level which consists of 4 levels. Each level of research has 10 plant samples. There were a total of 40 plant samples with the number of plant samples observed as many as 10 plants in each treatment. The water level factor (T) consists of 4 levels, namely: T1: Water Level 4 cm; T2: Water Level 8 cm; T3: Water Level 12 cm; T4: Water Level 16 cm.

2.4. Installation Design

The research was carried out in a greenhouse using a FONi technology, each installation consists of 10 pots. The FONi system consists of a water drum that functions as a nutrient water storage place which is then flowed through a 22 mm pipe to a control pot where there is an automatic float to regulate the water level which then nutrients water is flowed in each pot.

2.5. Research Implementation

2.5.1. Installation Preparation and Planting Media

The preparation for the FONi installation was by drilling holes in each bucket and water drum with a size of 27 mm and then installing a 22 mm grommet. On the control bucket an automatic water float was provided to measure the water level and then the installation of 22 mm PVC pipes was carried out and assembled as sketched in Figure 1. The plant medium used a mixture of soil, charcoal, husk and goat manure with a volume ratio (2:1:1).

2.5.2. Nutrient Water Procurement

Procurement and checking of nutritious water ws carried out every day. Nutrient water used AB Mix fertilizer with a nutrient concentration level in plants aged 0–7 DAP which was 500 ppm. At the age of 8–21 DAP the concentration was increased to 700 ppm, then at the age of 22–28 DAP the nutrient water concentration was increased to 900 ppm and at the age of 29 DAP the concentration of nutrient water was raised again to 1100–1300 ppm until the end of the study. The pH of nutrient water was set in the range of 5.5–6.5.

2.5.3. Planting

Japanese cucumber seeds were sown on seedling trays that have been filled with mixed soil and goat manure. Sowing was carried out for 7 days. After the plants are 7 days old, then the plants were transplanted to the FONi installation.

2.5.4. Pest Management

Plant disease pest control was carried out by spraying insecticides and fungicides on plants. Pest control used the insecticides Demolish 18 EC and Curacron 500 EC at a dose of 1 ml/L alternately. Disease management used the fungicide Antracol 70 WP 2 g/L. Spraying interval was carried out once every 7 days, if there was a surge in pest and disease attacks, the interval was accelarated to once every 3 days

2.6. Observation Variables

The observation variables carried out in this study included observation of vegetative phase and the generative phase. The observation variables in the vegetative phase included plant length (cm), stem diameter (mm) and number of leaves (leaves) observations are carried out since the plant is 7 DAP with an interval of 4 days, an analysis of chlorophyll using a SPAD (Soil Plant Analysis Development) meter, Observations in the generative phase, namely the fruit weight (g) and root length (cm) were conducted at each harvest throughout the harvesting period, with harvests occurring twice a week within each cycle until 5 harvest periods. Total irrigation volume (m^3) was calculated by adding up all the water added at the beginning to the end and subtracting the amount of water remaining at the end of the study. Environmental parameters were observed using the Automatic Weather Station (AWS) which was averaged every 10 days.

2.7. Data Analysis

The data obtained from each plant sample in each subsequent treatment was averaged. The data was presented in the form of a graph, a bar chart for the outcome variable, and a line chart for the growth variable.

3. RESULTS AND DISCUSSION

3.1. Environmental Parameters

Figure 2 presents environmental parameters that are divided into 10-day period. The 10-day period was determined based on the total age of Japanese cucumber begins from planting in December to harvest in February with a total length of 90 days. In each period presents the result of daily data that averages per 10 days. There was a decrease in rainfall, humidity, and the duration of solar irradiation in the 5th to 6th phases but the wind speed increased drastically, this shows that in this phase there are often cloudy sky conditions caused by wind blowing quite strongly.

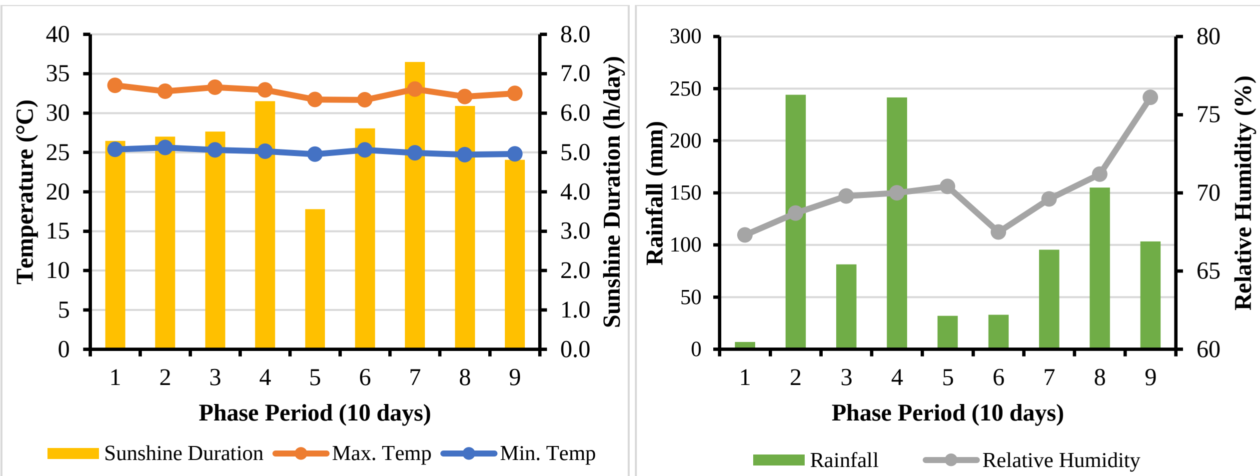

Figure 2. Environmental parameters at the research location

Environmental factors such as temperature, humidity, rainfall and the duration of sunlight greatly affect the evapotranspiration rate of Japanese cucumber plants, so that the water needs of plants and the growth of Japanese cucumber plants are largely determined by environmental factors. According to Noguchi *et al*. (2021), numerical modeling reveals that variations in the depth of a capillary barrier significantly alter the total soil water balance, thereby creating distinct differences in cumulative irrigation dynamics and root water uptake. That the water needs of plants will continue to increase as the plant ages, the availability of water greatly affects plant growth. Observation of the variable yield of Japanese cucumber plants at a water level of 8 cm showed that the plant was able to maintain a balance in water use to produce fruit. The application of irrigation levels results in different variations in water consumption. Differences in water consumption have no effect on quality and crop yields remain at stable and optimal levels as long as water needs are met (Guo *et al*., 2025).

The Unpowered Automatic Fertigator (FONi) serves as an automated irrigation system applying evapotranspiration principles without external electrical power. Integrated with precise water level control, it optimizes water use efficiency as well as various growth responses and productivity of Japanese cucumber. This research offers a practical benchmark for implementing eco-friendly, cost-effective precision agriculture that adapts to water scarcity challenges in urban farming.

3.2. Plant Length (cm)

Based on Figure 3, the highest numerical results were found in the treatment of water level 8 cm at the age of 7–27 DAP with a final length of 231,4 cm. The treatment of water level height of 4 cm obtained the shortest results at the observation of ages 15, 19, and 27 DAP with a final length of 206.7 cm. The difference in plant length between the treat-

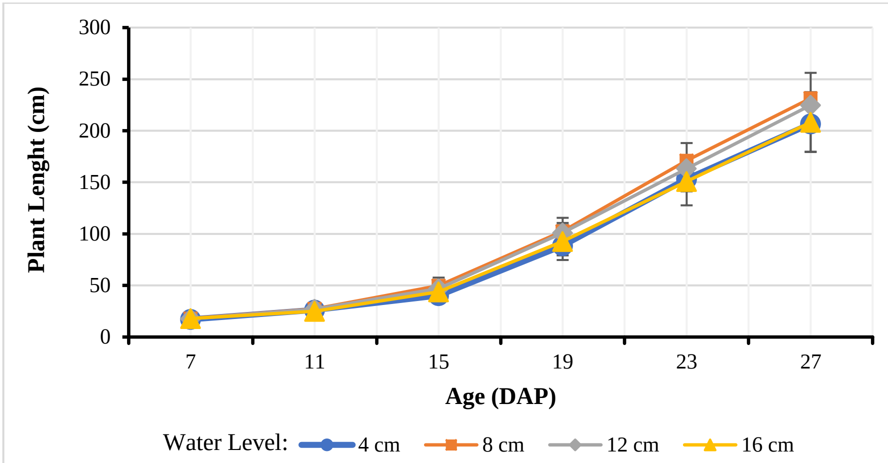

Figure 3. Growth of Japanese cucumber plant length under different water levels

Table 1. Representative regression equation and its R^2 plant length for different water level treatment

Treatment	Linear Regression	R^2	Exponential Regression	R^2
4 cm	$y = 39.328x - 48.985$	0.9197	$y = 9.5432e^{0.5293x}$	0.9866
8 cm	$y = 44.312x - 55.051$	0.9326	$y = 10.2e^{0.5424x}$	0.9884
12 cm	$y = 42.791x - 52.984$	0.9313	$y = 10.034e^{0.5387x}$	0.9880
16 cm	$y = 39.368x - 48.025$	0.9277	$y = 9.8575e^{0.5258x}$	0.9862

ment of 8 cm water level and the treatment of 4 cm is 24.7 cm, in the treatment of 12 cm which is 6.6 cm and in the treatment of 16 cm the difference is 23.2 cm. Based on the graph, the growth length of the plant in each treatment began to increase by the time the plant was age 15 DAP. Table 1 presents the regression equations for the growth length of Japanese cucumber as a function of plant age (x) modeled using linear and exponential regression. Both models show high R^2 values (> 0.90); however, the exponential growth model performs better, as it yields higher R^2 values (> 0.98) across all water level treatments.

These results show that the treatment of high water levels does not make plants experience water stress, either lack or excess water so that the photosynthesis process takes place properly. The condition of plant roots during the vegetative phase is still small, making plants maximize the water supply from the capillarity style of the soil porous to meet plant needs. Based on the results of the research of Kafle *et al.* (2025), plant growth will make a difference if the plant experiences water stress to a critical phase that makes the plant stressed. Japanese cucumber plants are able to maintain relatively uniform growth variables even though there are differences in water level treatment. The treatment of a water level of 8 cm is the optimal point because the capillary force can supply water needs well and soil aeration is maintained so that plants do not experience hypoxia. These results are in line with the research of She *et al.* (2022), if the water is too deep, it will be difficult for water to rise through the capillary gaps to supply plant needs.

The results of the observation of environmental parameters in the Table 1, the vegetative phase is located in the decade phase 1–3, based on these environmental parameters, the water needs of plants are not too high, so the available water is still enough to meet the needs of plants. The water needs of cucumber plants are met, making the plants grow well in the vegetative phase. Observation results the growth pattern of plant length modeled with the Gompertz pattern with a value of $y = 10.2e^{0.542x}$ and obtained a value of $R^2 = 98.84\%$ shows that plants at 7–27 DAP plants enter an exponential phase that is very active in dividing and extending vegetative cells before sloping when they begin to enter the generative phase. This is supported by the statement of Khan *et al.* (2024), the height of plants is affected by water, as water promotes vegetative growth of plants. Water as a constituent of the plant body affects the growth and development of plants. Water that functions as a material as well as a medium for transporting nutrients from the roots or the results of photosynthesis that occurs in leaves which are then channeled to sink organs such as root shoots and fruits (Gill *et al*., 2021).

3.3. Stem Diameter (mm)

Based on Figure 4, the best water level treatment is 12 cm at the age of 11, 15, 23 and 27 DAP with a final result of 8.9 mm. The lowest result was found in the treatment of a water level of 4 cm with a final result of 8.1 mm. The difference in stem diameter between the treatment of the water level of 8 cm and 12 cm with the treatment of 4 cm is 0.8 mm and the difference between the treatment of 16 cm is 0.2 mm. The results of the treatment of water level height of 8 cm and 12 cm did not differ in the observation of the age of 15 and 27 DAP. Based on the error bar, the stem diameter results from all treatments are quite uniform.

The result of the rod diameter is not too different at each water level treatment. The vegetative phase of high water level treatment does not cause stress resulting in stunted plant growth. Self-aeration at the treatment of water level heights of 8 and 12 cm makes plant roots grow and breathe well without experiencing stress due to water stress. According to Jin *et al.* (2023), the balance between moisture content and soil aeration determines the morphology, especially in plant roots. Plant roots that grow well can optimize the absorption of water and nutrients so that plant growth takes place optimally.

The water level in each treatment shows that the condition is still in optimal water availability conditions so that the plant does not experience a influence on the difference in stem diameter. Table 2 presents the regression equations for the growth of Japanese cucumber stem diameter as a function of plant age (x) using linear and logarithmic regression models. Both models show high R^2 values (>0.90); however, the logarithmic growth model performs better, as it yields higher R^2 values (>0.98) across all water level treatments. Based on the growth pattern observed with the logarithmic model with the equation $y = 2.6166\ln(x) + 3.3975$ with a value of $R^2 = 99{,}73\%$, it shows that division and vascular tissue occur very rapidly in plants aged 7–19 DAP and begin to slope at 23–27 DAP. Cucumber plants that receive frequent irrigation can increase the moisture content in the roots, thereby increasing the macronutrients absorbed by the cucumber plant from the soil (Taseen *et al.*, 2026). The growth of stem diameter is related to the activity of the cambium which is influenced by the results of photosynthesis. Based on results the study (Çeliktopuz *et al.*, 2025). The amount of irrigation significantly affects the diameter of the stem.

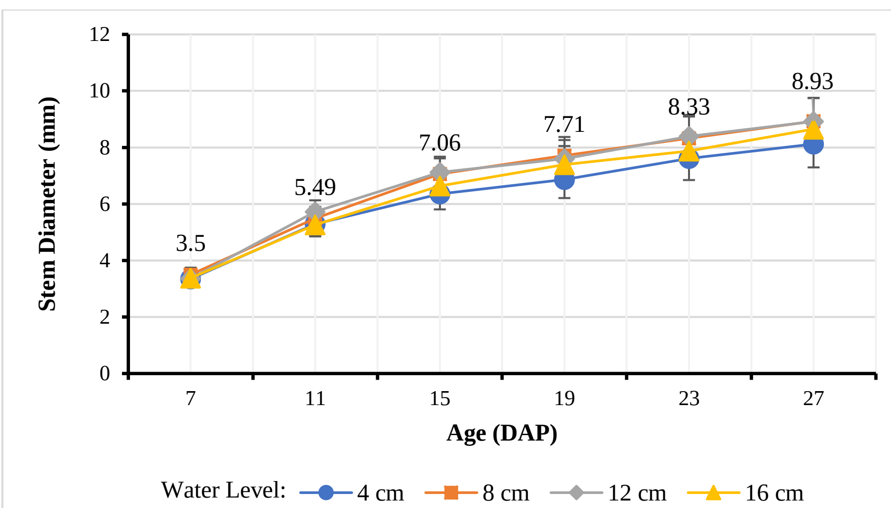

Figure 4. Growth Japanese cucumber stem diameter under different water levels

Table 2. Representative regression equation and its R^2 plant length for different water level treatment

Treatment	Linear Regression	R^2	Logarithmic Regression	R^2
4 cm	$y = 0.8949x + 3.1347$	0.9297	$y = 2.6166 \ln(x) + 3.3975$	0.9973
8 cm	$y = 1.0377x + 3.2047$	0.9251	$y = 3.0412 \ln(x) + 3.5019$	0.9967
12 cm	$y = 1.0369x + 3.2227$	0.9067	$y = 3.0652 \ln(x) + 3.4905$	0.9942
16 cm	$y = 0.998x + 3.0387$	0.9383	$y = 2.9046 \ln(x) + 3.3467$	0.9971

3.4. Number of Leaves

Based on Figure 5, in the observation of plants age 7 and 11 DAP, there was no difference in all levels of water level treatment. The number of leaves in the observation of 15 DAP began to show differences between levels of treatment. The final results showed that the largest number of leaves was found in the treatment of a water level height of 8 cm with an average number of leaves of 25.5 leaves. The lowest number of leaves is located at a water level of 4 cm with an average of 22.9 leaves. The difference in the number of leaves for treatment for water level height is 8 cm with water level treatment of 4 cm which is 2.6 sheets, treatment of 12 cm is 0.6 sheets, and treatment of 16 cm is 1,7 sheets. Based on the error bar, the number of Japanese cucumber planting leaves in each treatment is quite uniform.

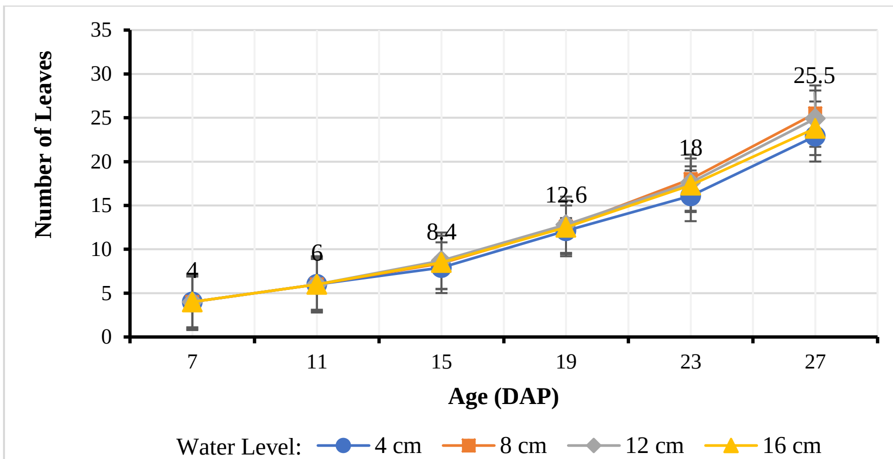

Figure 5. Growth Japanese cucumber number of leaves under different water levels

Table 3. Representative regression equation and its R^2 for number of leaves under different water level treatment

Treatment	Linear Regression	R^2	Exponential Regression	R^2
4 cm	$y = 3.6857x - 1.4$	0.9474	$y = 2.8965e^{0.346x}$	0.9974
8 cm	$y = 4.22x - 2.3533$	0.9429	$y = 2.8063e^{0.3704x}$	0.9994
12 cm	$y = 4.0971x - 2.0067$	0.9518	$y = 2.8668e^{0.3645x}$	0.9985
16 cm	$y = 3.9114x - 1.6733$	0.9568	$y = 2.8944e^{0.3566x}$	0.9983

Table 3 presents the regression equations for the Japanese cucumber growth of number of leaves modeled using linear and exponential regression. Both models show high R^2 values (> 0.90); however, the exponential growth model performs better, as it yields higher R^2 values (> 0.99) across all water level treatments. Plant growth is strongly influenced by photosynthetic activity which produces photosynthates that are useful as energy sunbers to form new tissues. Water plays an important role in maintaining plant balance through stomata regulation. The optimal environmental conditions in Table 3, the phase period 1–3 allow plants to photosynthesize well so that plants can grow optimally because plant evapotranspiration is maintained so that the roots can meet the plant's water needs. A suboptimal amount of water causes plants to increase the production of abscisic acid hormone (ABA) which causes stomata closure to reduce evapotranspiration in plants. The closure of stomata has an impact on the decrease in the rate of photosynthesis due to reduced CO_2 diffusion (Liu *et al.*, 2025). Observation results the growth pattern of number of leaves modeled with the Gompertz pattern with a value $y = 2.8063e^{0.3704x}$ with a value $R^2 = 99.9\%$, explains that plants are active in cell division for the formation of new leaves as Japanese cucumber plants age. Japanese cucumber plants are included in the category of photoperiod neutral, the length of sunlight and the intensity of sunlight still affect the photosynthesis rate of Japanese cucumber plants. According to research Cui *et al.* (2021), Light intensity affects plant growth and development, high light intensity conditions affect plant height, stem diameter, leaf area, number of leaves, and plant biomass.

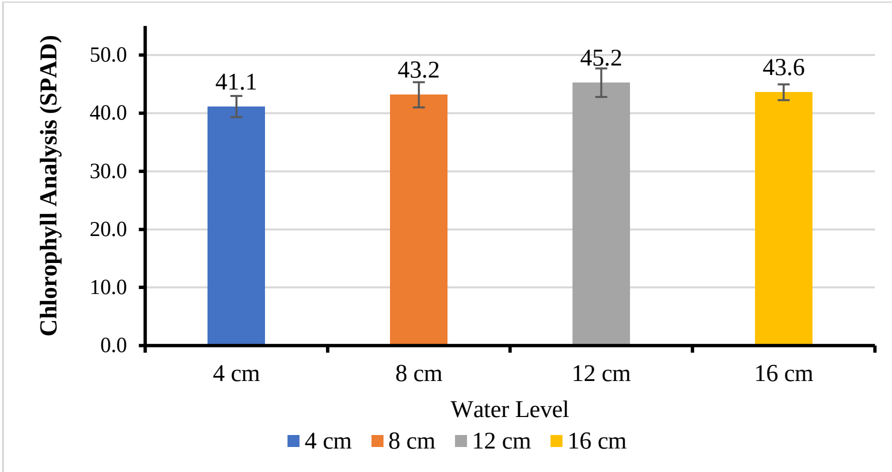

Figure 6. Chlorophyll analysis Japanese cucumber under different water levels

3.5. Analysis of Chlorophyll (SPAD)

Based on Figure 6, the water level treatment of 4 cm obtained the lowest chlorophyll content of 41.1 SPAD. Treatment of 8 cm water level results in chlorophyll levels with an average of 43.2 SPAD. The treatment of a water level of 12 cm obtained the highest results numerically with an average chlorophyll content of 45.2 SPAD. The treatment of a water level of 16 cm obtained an average chlorophyll level of 43.6 SPAD. The difference in chlorophyll levels for treatment of water level of 4 cm compared to treatment of 8 cm resulted in a difference of 2.1 SPAD or 5.11%. The water level treatment of 4 cm compared to the treatment of 12 cm is 4,1 SPAD or 9.98% and compared to the treatment of 16 cm, the difference is 2.5 SPAD or 6.08% 65 is greater than the treatment of water level of 4 cm. Based on the error bar, treatment of a water level of 16 cm results in uniform chlorophyll levels characterized by a short error bar line based on standard deviation.

The abundant availability of water increases chlorophyll levels because water is an important component in the photosynthesis process. The treatment condition of 4 cm water level high produces the lowest chlorophyll level compared to other treatments, this is because the roots have difficulty meeting the plant's water needs because water is difficult to reach, making the plant experience water shortages. These results are in line with the research of She *et al*. (2022), the results of SPAD chlorophyll analysis decreased as the groundwater depth decreased. The concentration of leaf chlorophyll became lower in cucumber plants that were given a water stress treatment which caused the rate of photosynthesis to decrease (Barickman *et al.,* 2019). The treatment of water level heights of 8, 12 and 16 cm shows that in this vegetative phase the plant does not experience hypoxia due to waterlogging. Good aeration conditions in the root area allow plants to absorb water and nutrients well to meet plant needs. The chlorophyll content in plants decreases significantly due to water stress, which affects the conductance of the stomata and interferes with some physiological processes of the plant. In plants during stress, the proteolytic enzyme chlorophyllase is active and degrades the chlorophyll content (Khan *et al*., 2024).

3.6. Fruit Weight (g)

Based on Figure 7, the treatment of the water level of 4 cm gets the lowest result, which is with an average weight of 272 grams. The treatment of 8 cm water level height gets the highest result, namely with an average weight of 394 grams. The treatment of water level of 12 cm and 16 cm is not much different from the average weight of 377 grams and 378 grams. The difference in the height of the water table results in a difference in the weight of the fruit. The difference in weight of the fruit with a water level height of 4 cm compared to the treatment of 8 cm is 122 grams or 44.85% heavier. In the treatment of 4 cm water level compared to the 12 cm treatment, the difference was 105 grams or 38.60% and in the 16 cm treatment the difference was 106 grams or 38.97% heavier than the 4 cm water level treatment. Based on the treatment bar error, the water level height of 8 cm resulted in the most uniform average weight of the fruit compared to other treatments.

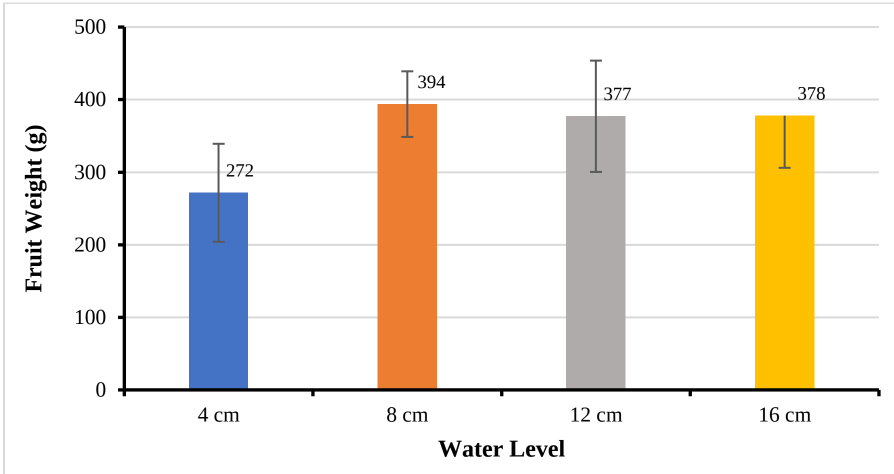

Figure 7. Fruit yield of Japanese cucumber plant under different water levels

Water availability affects the root conditions of Japanese cucumber plants. Suitable root conditions can support the physiological processes of Japanese cucumber plants. Treatment of 8 cm water level is the optimal water level level, because it can supply plant water needs well and also provide good aeration for roots to be able to breathe so that plant roots grow well and healthy without experiencing hypoxia due to lack or excess water. Lack of water causes plants to increase the production of the hormone abscisic acid (ABA) which can lead to the closure of the stomata to reduce evapotranspiration which has an impact on reduced photosynthesis yields (Liu *et al.*, 2025). Cell turgor is maintained at optimal water availability conditions so as to support cell division and enlargement as well as support nutrient transport and transfer of photosynthetic results to the main sink organs, namely shoots, roots and fruits. Efficient photosynthesis increases the accumulation of photosynthates which are then allocated to the formation and development of fruits. According to research Wen *et al.* (2021), Photosynthate produced through the process of photosynthesis is the main component that provides energy and substrate for the growth and development of plant organs, especially fruits as the main sink organs.

The treatment of water level regulates the aeration of the root area. Anoxic or hypoxic conditions in the rhizosphere cause cellular damage to root tissues, ultimately impairing the structural and reproductive development of the crop (Sadiku *et al*., 2022). Root areas that experience stress can cause plants to be suboptimal in absorbing nutrients that disrupt the photosynthesis process. Healthy root conditions can absorb water and nutrients well, keeping turgor cells awake and stomata on leaves open which has an impact on increasing chlorophyll levels and photosynthesis capacity. The increased photosynthesis capacity of the source organ results in abundant photoassimilate and is subsequently channeled to the sink organs such as fruits, which makes the weight of the fruit increase. Based on research Zhang *et al*. (2024), Leaf photosynthesis increases along with increased aeration rate in the plant's root area. The amount of water and aeration are correlated with each other and greatly affect the condition of the plant's roots. According to research Jin *et al*. (2023), The balance between water content and soil aeration determines the root morphology where the amount of dissolved oxygen (DO) in the soil correlates with root length, number of branching and dry weight of roots.

3.7. Root Length (cm)

Based on Figure 8, that in the treatment of the water level of 4 cm, the average root length is 42.27 cm. The treatment of 8 cm water level results in the best root length with an average length of 49.47 cm. The treatment of a water level of 12 cm showed an average root length of 39.92 cm and a water level of 16 cm showed the lowest result with an average root length of 38.57 cm. The difference in root length in the treatment height of the water level was 16 cm compared to the 4 cm treatment, which was 3.70 cm or 9.59% and compared to the 8 cm treatment, which was 10.90 or 28.26%. The difference in root length in water level is 16 cm compared to the 12 cm treatment, which is 1.35 cm or 3.50% of the treatment with a face height of 57 water 16 cm lower. Based on the error bar, the root length of the water table height of 4 and 8 cm is not uniform.

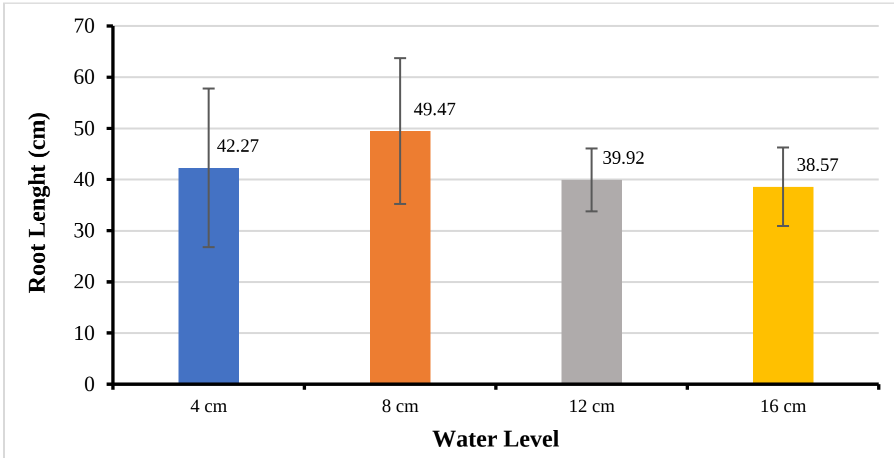

Figure 8. Root length of Japanese cucumber plant under different water levels

The treatment of low water level of 4 cm and 8 cm of roots is dominated by primary roots, while in the treatment of high water level of 12 cm and 16 cm, the roots form more fine roots. This is because the availability of water at low water levels is limited, so Japanese cucumber plants respond by extending the main roots and having a larger diameter to increase efficiency in reaching water at the water level. According to Jin *et al*. (2023), the balance between moisture content and soil aeration determines the root morphology where the amount of dissolved oxygen (DO) in the soil correlates with root length, number of branching and dry weight of the roots. Higher water level treatment, abundant availability stimulates the formation of lateral roots and fine roots to increase the absorption area to streamline water absorption under limited aeration conditions The water stagnation triggers the accumulation of ethylene and auxin, which then stimulates the formation of new adventitious roots (Qi *et al*., 2019).

3.8. Total Irrigation Volume (m^3)

Based on Figure 9, that in the treatment of the water level of 4 cm, the total irrigation volume is 0.0504 m3 in one planting period. The treatment of 8 cm water level uses the most total irrigation volume, which is 0.0603 m^3. The treatment of a water level of 12 cm uses the lowest total irrigation volume, which is 0,0503 m3. The treatment of a water level of 16 cm uses a total irrigation volume of 0.0536 m^3. The difference in total irrigation volume in the 12 cm treatment compared to the 4 cm treatment was 0.0002 m^3 or 0.40%. The difference in the 12 cm treatment compared to the 8 cm treatment was 0.0100 or 19.92% and compared to the 16 cm treatment, the difference was 0.0034 or 6.77% more water use than the 12 cm water level treatment.

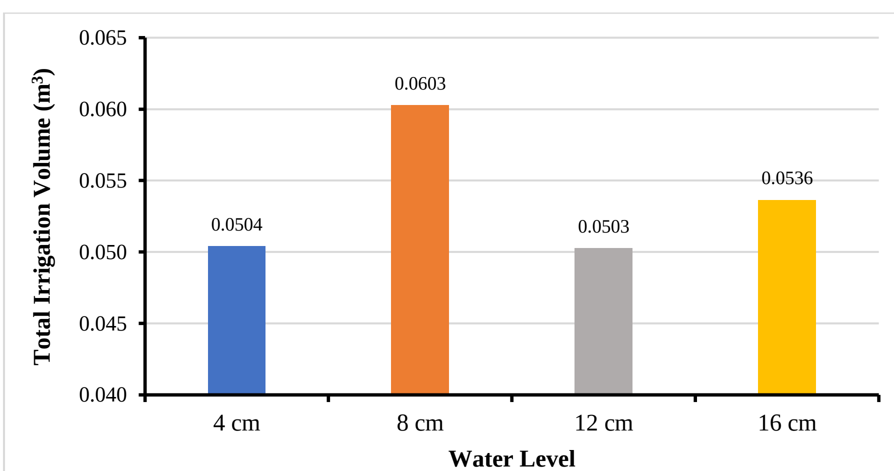

Figure 9. Total irrigation volume consumed by Japanese cucumber under different water level

The difference in water level treatment results in a variation in the total irrigation volume causing differences in the yield variables of Japanese cucumber plants because the plants are able to use water optimally. Healthy plant root conditions allow plants to absorb water and nutrients optimally. The high water consumption in the treatment of a water level of 8 cm is directly proportional to the variable of fruit yield observation, where the weight of the fruit is greater than other treatments. These results are in line with the research of Guo *et al*. (2025), the application of irrigation levels results in different variations in water consumption.

The novelty of this study lies in establishing an optimal hydraulic operating condition for the Unpowered Automatic Fertigator (FONi) system for Japanese cucumber. This study provides a crop-specific optimization of the FONi system by evaluating different water levels for Japanese cucumber cultivation under greenhouse conditions. Unlike previous studies that primarily demonstrated the feasibility of FONi for water and nutrient delivery, this research establishes the relationship between water level, root-zone conditions, vegetative growth, root development, irrigation use, and fruit production. The results identify an 8 cm water level as the most favorable condition, achieving the highest plant growth, root length, and fruit weight while maintaining an appropriate balance between water availability and root-zone aeration. These findings provide practical operational guidance for improving the performance of electricity-free fertigation systems and support the development of energy-efficient and water-conscious cultivation technologies for protected and urban agriculture.

4. CONCLUSIONS

The water level treatments influenced the growth, yield, root development, and irrigation water use of Japanese cucumber cultivated using the Unpowered Automatic Fertigator (FONi). Among the tested treatments, the 8 cm water level produced the most favorable overall response, as indicated by the highest plant length (231.43 cm), number of leaves (25.5 leaves), fruit weight (394 g), and root length (49.47 cm). This water level provided a suitable balance between water availability and root-zone aeration, thereby supporting water and nutrient uptake as well as vegetative and generative growth. Therefore, maintaining an 8 cm water level is recommended for Japanese cucumber cultivation using FONi under greenhouse conditions similar to those of this study.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

Not applicable. The authors did not use any generative AI tools or services in the preparation of this manuscript. All content is entirely the intellectual work of the authors.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
MANU			✓			✓	✓	✓	✓		✓			
NT	✓	✓		✓						✓		✓		
FS	✓	✓		✓						✓		✓		
CA	✓	✓		✓			✓			✓		✓		

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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