HAYATI
Journal of Biosciences

Vol. 33 No. 4, July 2026 1062-1073
DOI:10.4308/hjb.33.4.1062-1073
ISSN: 1978-3019
EISSN: 2086-4094

Research Article

Enhancing Growth and Macronutrient Efficiency Through Rainfed Fertigation in Greenhouse Hydroponic Leafy Vegetables

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ARTICLE INFO

Article history:
Received October 3, 2025
Received in revised form January 7, 2026
Accepted April 20, 2026
Available Online May 21, 2026

KEYWORDS:
fertigation,
hydroponic,
leafy vegetables,
macronutrients,
rainwater harvesting

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ABSTRACT

Reliability of hydroponic crop cultivation in greenhouses requires sustainable management of nutrients and water. Nutrient supply based on rainwater harvesting is a viable strategic practice for crop cultivation systems. However, further exploration of the effects on physiological responses and crop yields across various nutrient concentrations is important to improve usage efficiency. This study examined the impact of macronutrient deficiencies on the growth and yield of leafy vegetables using a rainwater-harvesting. Rainwater harvested from the greenhouse roof was fully utilized as a water source for the nutrient solution applied to the plants. Pak choi (*Brassica rapa* var. *chinensis*) and lettuce (*Lactuca sativa* L. var. *crispa*) were cultivated hydroponically using the Nutrient Film Technique system under varying macronutrient concentrations (25, 50, 75, and 100%) based on a modified Hoagland standard solution. Additional treatment was applied as a macronutrient deficiency, adjusted to the macronutrient content of the harvested rainwater. The number of leaves, SPAD index, fresh weight, and nutrient status were measured for each treatment every three days after planting until harvest. Pak choi plants showed greater tolerance to low levels of macronutrient deficiency, whereas lettuce was only tolerant of low levels of potassium deficiency. Rainwater-based nutrient supply maintained the growth and yield of leafy vegetables without a significant difference compared to the control, while reducing macronutrient inputs by 0.21-24.02%. These results indicate that macronutrient concentrations can be lowered to enhance fertilizer use efficiency and prioritize economic benefits.

1. Introduction

The growing demand for sustainable agriculture has driven the adoption of efficient cultivation practices, particularly in the management of water and nutrients. Hydroponic cultivation in controlled greenhouse environments offers an effective solution to enhance crop production. Various hydroponic cultivation methods have been practiced globally, including floating systems, nutrient film technique, drip systems, and aeroponics (Sambo *et al.* 2019). Barbosa *et al.* (2015) reported that hydroponic cultivation of lettuce in greenhouses yields 11 ± 1.7 times higher compared to conventional cultivation. Hydroponic practices also accelerate growth by up to 50% and enhance water use efficiency by up

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to 80% compared to conventional practices (Swain *et al.* 2021).

However, the productivity of hydroponically cultivated plants depends heavily on maintaining a continuous supply of water and nutrients. Inefficient nutrient uptake or nutrient limitations can reduce the photosynthetic rate during both vegetative and generative phases (Seepaul *et al.* 2016; Erniati *et al.* 2024; Suharto *et al.* 2025). The lower and upper thirds of the leaves will show more evident symptoms of chlorosis and necrosis due to nutrient deficiency. Conversely, excess nutrients can cause toxicity, disrupt the balance of other elements, and increase the risk of environmental pollution due to nutrient leaching (de Souza Osório *et al.* 2020).

Essential macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur are required to enhance plant growth and yield. Other elements cannot substitute for their presence in nutrient solutions. Veazie *et al.* (2020) reported that macronutrient deficiency in *Brassica rapa* var. *chinensis* reduced dry weight, chlorophyll and carotenoid contents, and leaf anthocyanin concentration. Specifically, Veazie *et al.* (2022) found that nitrogen deficiency stunted growth and reduced plant weight, while phosphorus deficiency exhibited stunted growth, a dark green color, and dullness. Furthermore, potassium deficiency initially manifested as stunted growth and marginal chlorosis of the lower leaves.

In addition to macronutrients, micronutrients are still required for plant growth and production, although they are smaller in quantity. The impact of micronutrient concentrations was evaluated by Cockson *et al.* (2021), who found that micronutrients had different effects on the growth and yield of *Brassica carinata*, with boron having the greatest impact among the other elements. Boron (B) deficiency can result in the death of the apical meristem and reduce siliqua or seed formation. Micronutrients serve a critical role in regulating chlorophyll synthesis, thereby directly enhancing the efficiency of photosynthetic rates. Although the responses of plant growth and yield to nutrient uptake have been extensively investigated, further exploration of individual elements remains essential to enhance nutrient use efficiency and productivity.

Additionally, sufficient water availability determines the efficiency of nutrient uptake by cultivated plants. Abdelmoneim *et al.* (2013) found that water deficit in maize (*Zea mays* L.) decreased protein concentration by 29.3% and phosphorus uptake by 72.09% compared with normal irrigation treatment. Rainwater harvesting from greenhouse rooftops serves as an effective strategy to ensure sustainable water availability in fertigation systems (Islam *et al.* 2013; Ertop *et al.* 2023). Rainwater harvesting practices for fertigation have been implemented across various regions and storage methods. Studies have reported that this approach can meet 60-100% of the crop water requirement (Singh *et al.* 2019; Londra *et al.* 2022; Boyaci *et al.* 2024).

Globally, Piemontese *et al.* (2020) reported that rainwater harvesting can supply more than 60% of crop water requirements and enhance yield by 60-100%. Sirait *et al.* (2024) investigated the potential of rainwater harvesting for greenhouse vegetable cultivation, demonstrating that it could meet the water needs of 2.79 L•m^{-2} per day and produce a surplus of up to 18.91 m^3. Furthermore, rainwater was found to contain several macronutrients that could potentially be utilized by plants, including nitrate (0.37-11.57 mg•L^{-1}), ammonium (0.1-0.32 mg•L^{-1}), phosphate (0.001-0.19 mg•L^{-1}), calcium (3.36 mg.L^{-1}), sulphate (2.00-8.89 mg•L^{-1}), and magnesium (0.23-3.00 mg•L^{-1}) (Handriyono and Dewi 2018; Khairani 2018; Putra 2018; Asnaning *et al.* 2019; Prihadi *et al.* 2019). In addition, several micronutrients were also detected, such as iron (0.01-0.26 mg•L^{-1}), manganese (0.01-0.1 mg•L^{-1}), and zinc (0.07 mg•L^{-1}) (Untari and Kusnadi 2015; Zdeb *et al.* 2020).

The reliability of rainwater harvesting systems for supplying crop water requirements has been demonstrated in several studies. However, most studies focus on quantifying harvestable water volume and water savings in domestic or open-field agriculture. Studies on the physiological responses of hydroponic plants and their impact on yields remain limited, including evaluations of rainwater as a nutrient solubilizer to enhance fertilization efficiency. Providing the proper proportions of macronutrients is essential to maximize plant growth and yield, prevent fertilizer overuse, and optimize economic benefits. This study examines the effects of macronutrient concentrations on the growth and yield of hydroponically grown leafy vegetables under rainfed fertigation in a greenhouse. The use of elements contained in rainwater was tested in experiments to minimize macronutrient input.

2. Materials and Methods

2.1. Study Area

In this study, a piggyback-type greenhouse with an area of 72 m^2, located at the Siswadhi Soepardjo Field

Laboratory, IPB University, was used as the experimental site. Rainwater harvesting was conducted through a 112 m^2 greenhouse roof covered with polyethylene film, which effectively served as a catchment area (Figure 1). In addition, rainfall depth data for the study area were used to estimate the potential volume of rainwater that could be harvested from greenhouse roofs. Furthermore, a water storage tank with a capacity of 2000 L was used to provide fertigation during the experimental period from March to April 2025.

The instruments used include a DN50 flowmeter sensor to measure harvested rainwater volume, an EZ9908 EC/pH meter to monitor nutrient solution conditions, and a Minolta SPAD-502 meter to measure leaf SPAD values. Additional observations of greenhouse microclimate conditions were conducted using a Davis Vantage Pro2 automatic weather station, with data stored in real time on a server for analysis (Saptomo *et al.* 2023). Finally, experiments were conducted on pak choi (*Brassica rapa* var. *chinensis*) and lettuce (*Lactuca sativa* L. var. *crispa*) cultivated hydroponically using the Nutrient Film Technique (NFT) system. This method was applied to ensure high-quality leafy vegetable production while reducing water use by 70-90% of water use (Sharma *et al.* 2018; Rani *et al.* 2023).

2.2. Harvested Rainwater Volume

The volume of captured rainwater from greenhouse roofs was measured using a calibrated 2-inch DN50 flowmeter installed at the storage tank inlet. Measurements were conducted in real time throughout the experimental period, including rainfall events, and were subsequently accumulated to determine the daily harvested volume. Additionally, rational methods are applied to calculate the monthly potential harvested volume (Equation 1). This calculation estimated the potential volume of rainwater that could be harvested for use in the greenhouse fertigation system.

$$Q = C\,I\,A$$

Where Q is the harvested rainwater volume (m^3), C is the coefficient of roof runoff, I is the rainfall intensity (mm), and A is the greenhouse roof area (m^2). According to greenhouse roof materials, the coefficient of roof runoff was selected as 0.8 (MoE/UNDP 2016; Wang *et al.* 2021). Meanwhile, rainfall data for the period 2004-2023 were obtained from the Dramaga Climatology Station in Bogor, which represents the conditions of the research location.

2.3. Fertility Treatments and Experimental Designs

The treatments were divided into eight groups, and the concentrations of individual macronutrients were based on the modified Hoagland standard solution (Hoagland and Arnon 1950; Veazie *et al.* 2022). While

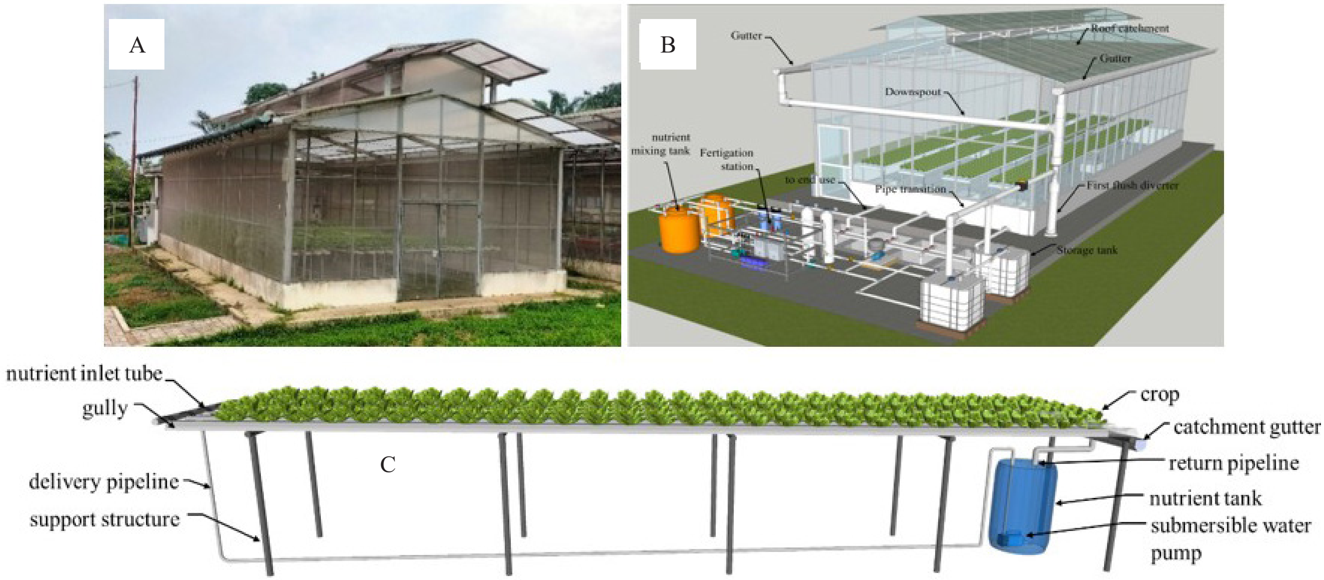

Figure 1. (A) The greenhouse used for experimental cultivation of leafy vegetables using the Nutrient Film Technique hydroponic method, (B) architecture of a rainwater harvesting system integrated with a fertigation system in a greenhouse, and (C) schematic diagram of a Nutrient Film Technique (NFT) hydroponic system installation

macronutrient concentrations of macronutrients varied, all other elements were held constant across treatments, as shown in Table 1. Solution A contains a compound blend of calcium nitrate ($Ca(NO_3)_2$), potassium nitrate (KNO_3), sodium nitrate ($NaNO_3$), and iron chelate (Fe-EDTA). Furthermore, solution B contains monopotassium phosphate (KH_2PO_4), magnesium sulfate ($MgSO_4$), ammonium sulfate ($(NH_4)_2SO_4$), micro manganese (Mn-EDTA), and vitaflex micro-complexes to obtain copper (Cu), zinc (Zn), boron (B), and molybdenum (Mo) elements.

In this experiment, a total of 100 leafy vegetable plants were allocated to each treatment in four replicates for a 40-day life cycle. This was initiated by sowing seeds in rockwool, supplied with water, after which the 10-day-old seedlings were transplanted into an NFT gully using 5.2 cm net pots, with a planting spacing of 18.5×15.0 cm. Electrical conductivity of nutrient solutions was conducted gradually from 1.0 to 2.5 dS•m^{-1}, and pH was maintained at 5.5-6.5 (Sharma *et al.* 2018; Conversa *et al.* 2021; Swain *et al.* 2021). Measurements of leaf numbers, fresh weight, nutrient solution status, and SPAD values were carried out every three days after transplant, in the morning between 6:00 and 9:00 AM (Kumar *et al.* 2021).

Leaf number was measured non-destructively on 24 sample plants per treatment, by counting the number of fully developed true leaves on each plant. Leaves counted were those that had come out of the growth point and possessed a lamina clearly distinct from the bud. Meanwhile, leaves that were still in the form of primordia or buds were not included in the leaf count. Furthermore, the parameters measured in the nutrient solution include pH and electrical conductivity, measured with an EZ9908 EC/pH meter calibrated to ensure accuracy. Nutrient solution levels in the tank were measured with a calibrated ruler to indicate nutrient solution consumption of plants. Concurrently, the quality of raw water from rainwater harvesting was also measured for electrical conductivity and pH.

In terms of SPAD index measurement, it was conducted on healthy leaves using a Minolta SPAD-502 meter (SPAD-502; Konica Minolta Sensing, Osaka, Japan) (Loh *et al.* 2002; Hlavinka *et al.* 2013). Measurements were taken on the third leaf from the top of each plant, with three locations per leaf (about 0.5 cm from the edge of a leaf), and were averaged (Debaeke *et al.* 2006; Valentinuzzi *et al.* 2015; Veazie *et al.* 2020). The instrument was calibrated before measurement using the manufacturer-supplied Plant Pen reflectance reference, without inclusion of a sample. The SPAD index was measured only on pak choi, as lettuce leaves are thinner and more fragile and prone to damage when repeatedly measured with the clip of a SPAD-502 clip.

2.4. Data Analysis

This study used IBM® SPSS Statistics 23.0 to perform a one-way ANOVA and compare means. Duncan's multiple range test was conducted as a post-hoc analysis when the F-test indicated significant

Table 1. Concentrations for macronutrients used to experiment on the growth of *Brassica rapa* var. *chinensis* and *Lactuca sativa* L. var. *crispa* over its life stages

Treatments	Nutrient element composition (mg•L^{-1})*					
	N	P	K	Ca	S	Mg
Control	150.00	20.00	150.00	75.00	40.00	25.00
RWH**	147.56	19.97	148.52	70.59	33.20	22.79
N-75%	112.50	20.00	150.00	75.00	40.00	25.00
P-75%	150.00	15.00	150.00	75.00	40.00	25.00
K-75%	150.00	20.00	112.50	75.00	40.00	25.00
N-50%	75.00	20.00	150.00	75.00	40.00	25.00
P-50%	150.00	10.00	150.00	75.00	40.00	25.00
K-50%	150.00	20.00	75.00	75.00	40.00	25.00
	Micronutrients for all treatments (mg•L^{-1})					
	Fe	Mn	Cu	Zn	B	Mo
All treatments	4.02	0.99	0.19	0.20	0.49	0.01

*Values indicated the composition of individual macronutrients adjusted based on modified Hoagland solutions for each treatment. **RWH represents a treatment that utilizes the macroelements contained in rainwater harvested from greenhouse roofs, which was obtained from laboratory analysis (2.44 mg•L^{-1} N, 0.03 mg•L^{-1} P, 1.48 mg•L^{-1} K, 4.41 mg•L^{-1} Ca, 6.80 mg•L^{-1} S, 2.21 mg•L^{-1} Mg). The macronutrient composition in RWH treatment was adjusted based on the macronutrient content of the harvested rainwater and the control differences ($P \leq 0.05$) among the means. The analysis results are presented in tables and graphs to clarify the interpretation of differences among treatments and support the conclusions.

3. Results

3.1. Greenhouse Microclimate Conditions

The air temperature, relative humidity, and solar radiation were the main parameters of microclimate conditions measured in this study. They were measured in real time at 30-minute intervals, conducted from transplanting to late-stage plants. This was conducted to investigate the suitability of greenhouse microenvironments for leafy vegetable growth. Natural ventilation was applied throughout the experiment to control temperature and humidity without additional energy consumption. The means of each measurement time interval were determined to represent each parameter, as given in Figure 2.

Air temperatures ranged from 24.0°C to 32.9°C, with a mean of 27.7°C. The air temperature increased gradually from 8:30 AM, reaching its peak at 12:30 PM. At midday, the air temperature approached 32.9°C due to high-intensity sunlight. Meanwhile, the mean measured solar radiation was 44.3 W•m^{-2}, with a maximum of 175.4 W•m^{-2}. Furthermore, the measured relative humidity ranged from 72.1% to 87.3%, with an average of 82.7%. The patterns of temperature and solar radiation peaked at midday, whereas relative humidity peaked at night and persisted until dawn.

3.2. Harvested Rainwater Volume

In this study, the daily harvested volume was measured, stored in water tanks, and fully utilized to supply fertigation throughout the experimental period. The greenhouse roof area is fully utilized as a catchment area, maximizing harvest volume via gutters and collection channels. Furthermore, the optimal storage water tank capacity was applied to enhance system reliability based on the potential harvested volume. Figure 3 shows the amount of rainwater captured in the greenhouse as a function of rainfall depth and roof area.

Rainwater harvesting conducted from March 1 to April 9, 2025, produced a cumulative volume of 30422,79 L, equivalent to 271.63 L•m^{-2} (Figure 3A). The mean daily harvested volume reached 760,57 L•day^{-1}, with a maximum of 8596,70 L•day^{-1} and a minimum of 0 L•day^{-1} on rainless days. The maximum harvested volume was recorded on March 18, 2025, enabling it to meet demand during the dry season. Meanwhile, the mean harvested potential volume based on monthly rainfall depth was 25.43 m^3 per month, equivalent to 227.02 L•m^{-2} (Figure 3B). Harvested volume was filtered through a roof drain to remove debris before storage, ensuring water was free from leaves and similar impurities.

3.3. Nutrient Solution Conditions

Measurements of nutrient solution conditions revealed significant differences among treatments, as shown in Figure 4. Electrical conductivity of the nutrient solutions

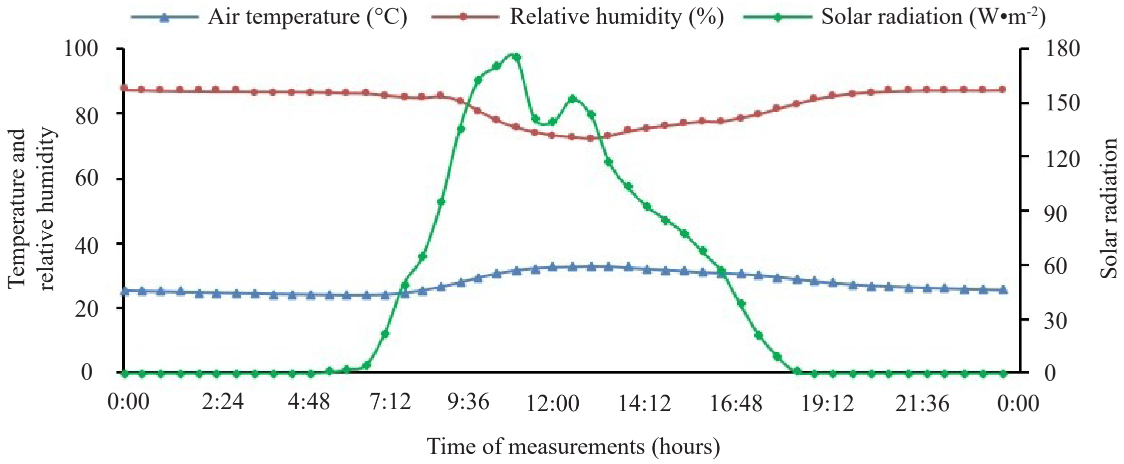

Figure 2. Air temperature, relative humidity, and solar radiation conditions in the greenhouse were measured using a Davis Vantage Pro2 automatic weather station

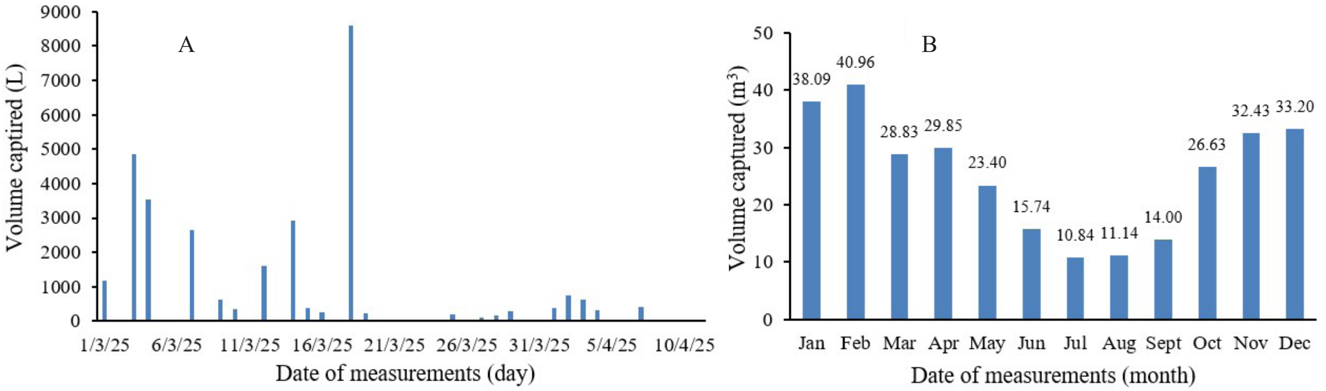

Figure 3. Rainwater volume harvested from a 112 m^2 greenhouse roof for fertigation supply. (A) daily actual volume harvested during the experimental period, (B) mean monthly potential harvested volume based on rainfall depth data from 2004 to 2023

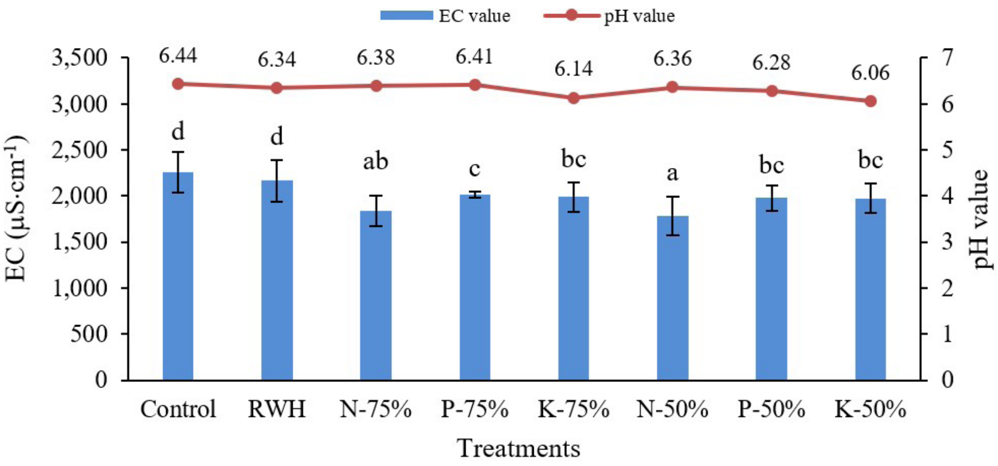

Figure 4. Nutrient solution concentration for each treatment was measured throughout the experimental period. Significant differences at $P \leq 0.05$ are indicated by different letters above the bars, while the same letters indicate a lack of statistically significant differences. Bars represent the means and standard deviation

ranged from 1782.36 to 2253.45 µS•cm^{-1}, reflecting treatment-related variations. The control and RWH treatments exhibited the highest electrical conductivity among all treatments, with values of 2253.45 µS•cm^{-1} and 2166.64 µS•cm^{-1}, respectively. Meanwhile, the N-50% treatment showed the lowest value among the treatments, at 1782.36 µS•cm^{-1} (Figure 4). Furthermore, the mean pH of the nutrient solution ranged from 6.06 to 6.44, with the control treatment exhibiting the highest value, and the K-50% treatment the lowest.

In terms of nutrient solution consumption (Figure 5), the control treatment consumed 212 L with a total nutrient input of 1425 mL. Treatment RWH consumed slightly lower than the control, at 209 L with a total nutrient input of 1413 mL. Treatments of N-75%, P-75%, and K-75% reduced nutrient solution consumption to 205 L (1385 mL), 200 L (1356 mL), and 193 L (1320 mL), respectively. In the 50% concentration treatment, nutrient solution consumption decreased to 182 L (1277 mL), 187 L (1282 mL), and 180 L (1256 mL) for N-50%, P-50%, and K-50%. Additionally, the raw rainwater harvested for nutrient mixing had an electrical conductivity of 97.88 µS•cm^{-1} and a pH of 6.82.

3.4. Growth and Yield

Plant growth was evaluated quantitatively based on the number of leaves, fresh weight, and SPAD index measured at each observation. The measurement results showed that pak choi and lettuce responded differently to various treatments. These differences indicate the effects of variations in macronutrient concentrations on the growth of both crops. Significant differences in leaf number were observed between the macronutrient concentration treatments and the control (Table 2).

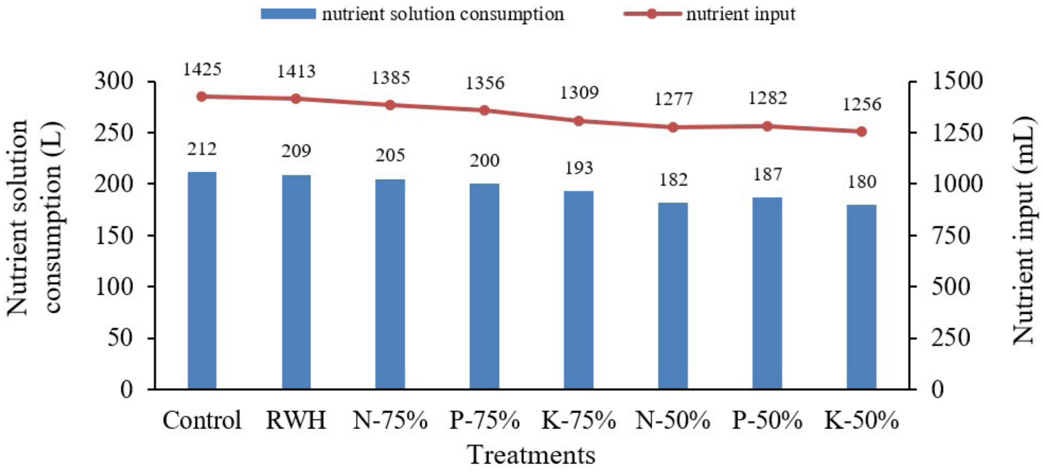

Figure 5. Total nutrient use for each treatment was measured cumulatively during one growing season of leafy vegetables, which included all growth stages from planting to harvest (30 days after planting)

Table 2. Effect of treatments on leaf number of pak choi (*Brassica rapa* var. *chinensis*) and lettuce (*Lactuca sativa* L. var. *crispa*) observed 30 days after planting

Treatments	*n*	Leaf number of pak choi (leaves)			Leaf number of lettuce (leaves)		
		Min	Max	Mean	Min	Max	Mean
Control	24	21.00	23.00	22.33±0.56^{f}	20.00	21.00	20.33±0.48^{f}
RWH**	24	21.00	23.00	22.04±0.75^{ef}	18.00	22.00	19.79±1.28^{ef}
N-75%	24	21.00	22.00	21.38±0.49^{e}	12.00	19.00	16.29±1.43^{c}
P-75%	24	17.00	25.00	20.29±1.78^{d}	16.00	19.00	16.88±0.95^{c}
K-75%	24	17.00	22.00	19.67±1.37^{cd}	18.00	20.00	19.21±0.83^{e}
N-50%	24	17.00	21.00	18.63±1.28^{b}	13.00	16.00	14.46±0.78^{a}
P-50%	24	15.00	25.00	19.04±2.24^{bc}	13.00	17.00	15.17±1.13^{b}
K-50%	24	16.00	19.00	17.71±0.81^{a}	16.00	20.00	18.08±1.10^{d}

*Significant differences at P ≤ 0.05 are indicated by different letters in the same column, while the same letters indicate a lack of statistically significant differences. These values were obtained from measurements of sample plants and were averaged

The RWH treatment had a number of leaves that was not significantly different from the control, both in pak choi and lettuce. In pak choi, the N-75% produced the highest value, followed by the P-75% and K-75%. For lettuce, the K-75% treatment had the highest number of leaves compared with the N-75% and P-75% treatments. The other treatments showed significant differences with the control, with the N-50% treatment having only 18.63 ± 1.28 leaves in pak choi and 14.46 ± 0.78 leaves in lettuce. Furthermore, phosphorus and potassium deficiencies had different effects, although both differed significantly from the control. Subsequently, fresh weight was measured to investigate the effect of each treatment on crop yield, as shown in Table 3.

The fresh weight produced by RWH was nearly equivalent to the control, with no significant differences in pak choi or lettuce. In pak choi, RWH produced a fresh weight of 242.12 ± 15.52 g, representing only a 0.84% decrease compared to the control (244.17 ± 6.91 g). The N-75% treatment remained relatively high with only a 3.71% reduction, whereas the P-75% and K-75% treatments exhibited reductions of 9.77% and 13.76%, respectively. A significant reduction was observed at 50% deficiency, with the greatest decrease observed in the K-50 treatment at 26.12%. Furthermore, the N-50% and P-50% treatments reduced the fresh weight of pak choi by 22.35% and 19.72%, respectively.

In lettuce, the RWH treatment showed no significant difference from the control, with only a 2.8% reduction in fresh weight. The lowest fresh weight was found in the N-50% treatment, representing a reduction of 55.99% compared to the control. At the N-75% treatment, fresh weight was reduced by 36.37% to 83.58 ± 6.74 g, while P-75% resulted in a 32.96% reduction to 88.06 ± 6.85 g. In contrast, the K-75% treatment maintained a relatively higher fresh weight, with only an 11.92% reduction to 115.70 ± 16.27 g. Meanwhile, a 50% macronutrient deficiency reduced fresh weight under the P-50% and

K-50% treatments of 44.83% and 26.27%, respectively. Additionally, chlorophyll status was assessed using SPAD index measurements of pak choi, which provided more consistent and stable readings without tissue damage during repeated measurements (Table 4).

Table 4 shows that SPAD values increased across all treatments as the plants aged. At 30 days after planting, the SPAD index in RWH was not significantly different from the control, with only a slight decrease of 0.22. Treatments at 75% concentration (N-75%, P-75%, K-75%) produced SPAD index intermediate between the control and 50% deficiency treatments, and significantly different from the control. The decrease was relatively small, ranging from 2.7% to 6.4%, and the values consistently remained above 40.00. Meanwhile, a significant decline in the SPAD index was observed under 50% deficiency of N, P, and K (N-50%, P-50%, K-50%), with reductions of 9.3%, 9.1%, and 11.8%, respectively.

4. Discussion

Temperature in the greenhouse remained within the optimal range for leafy vegetable growth (15-32°C) (Rakesh *et al.* 2020). High growth temperatures (40°C) can inhibit enzyme function, thereby significantly reducing the growth and yield of leafy vegetables (Jasper *et al.* 2020). Relative humidity indicated a sufficiently moist environment to sustain transpiration balance and support the physiological processes of the plants. Excessive humidity may increase the risk of pathogen spread, such as Botrytis and other plant diseases (Gruda 2005). Solar radiation remained at levels sufficient to optimize nutrient uptake, photosynthetic rate, and biomass accumulation, despite fluctuations of up to 175.4 W•m^{-2} (Fu *et al.* 2017; Sublett *et al.* 2018). Meanwhile, excessive irradiation of 236.60 kW•m^{-2} can cause tipburn in lettuce (Wissemeier and Zühlke 2002). The observed reduction in fresh weight was more closely associated with nutrient deficiency, as evidenced by enhanced responses in treatments with adequate nutrient availability.

The rainwater harvesting system was able to fully meet the total water demand of 1881.60 L after accounting for a 20% leaching factor (Sirait *et al.* 2024). Boyacı *et al.* (2024) and Bafdal *et al.* (2020) reported that rainwater harvesting could meet crop water requirements and

Table 3. Effect of macronutrient concentration on fresh weight of pak choi (*Brassica rapa* var. *chinensis*) and lettuce (*Lactuca sativa* L. var. *crispa*) measured 30 days after planting

Treatments	*n*	Fresh weight of pak choi (g)			Fresh weight of lettuce (g)		
		Min	Max	Mean	Min	Max	Mean
Control	24	231.70	256.70	244.17±6.91^{f}	126.23	134.83	131.35±2.62^{f}
RWH**	24	212.40	267.60	242.12±15.52^{ef}	119.43	140.03	127.69±5.65^{f}
N-75%	24	224.50	246.00	235.10±6.24^{e}	70.93	95.53	83.58±6.74^{c}
P-75%	24	185.80	240.00	220.33±16.31^{d}	78.73	108.63	88.06±6.85^{c}
K-75%	24	183.30	231.70	210.57±12.57^{c}	94.83	152.23	115.70±16.27^{e}
N-50%	24	152.20	239.80	189.59±22.14^{b}	46.23	71.33	57.81±7.64^{a}
P-50%	24	157.60	227.30	196.01±17.67^{b}	61.93	83.63	72.46±6.24^{b}
K-50%	24	159.80	215.40	180.38±14.94^{a}	81.13	110.53	96.85±8.17^{d}

*Significant differences at P ≤ 0.05 are indicated by different letters in the same column, while the same letters indicate a lack of statistically significant differences. These values were obtained from measurements of sample plants and were averaged

Table 4. SPAD index values of pak choi (*Brassica rapa* var. *chinensis*) were measured at 9, 16, 23, and 30 days after planting for each treatment

Treatments	*n*	SPAD index value (SPAD units)			
		9-DAP	16-DAP	23-DAP	30-DAP
Control	24	35.48±0.76^{d}	37.48±1.00^{d}	39.99±1.49^{d}	42.98±1.65^{f}
RWH**	24	35.46±1.04^{d}	37.24±1.04^{d}	39.88±1.28^{d}	42.76±1.60^{ef}
N-75%	24	33.70±1.38^{c}	36.44±1.31^{c}	38.60±1.40^{c}	41.81±2.01^{de}
P-75%	24	33.39±1.26^{c}	36.02±1.30^{c}	38.10±1.76^{c}	41.14±2.09^{cd}
K-75%	24	33.55±1.10^{c}	35.75±1.21^{bc}	37.97±1.02^{c}	40.18±1.44^{c}
N-50%	24	31.74±1.80^{a}	34.28±1.44^{a}	36.20±1.15^{ab}	38.98±1.16^{b}
P-50%	24	32.60±1.07^{b}	35.08±1.31^{b}	36.82±1.45^{b}	39.01±1.86^{b}
K-50%	24	31.69±1.10^{a}	34.14±1.27^{a}	36.00±1.20^{a}	37.90±1.53^{a}

*DAP: days after planting. **Significant differences at P ≤ 0.05 are indicated by different letters in the same column, while the same letters indicate a lack of statistically significant differences. These values were obtained from measurements of sample plants and were averaged provide economic benefits to hydroponic enterprises in greenhouses. The rainwater harvesting system was equipped with a simple filtration unit, and the harvested rainwater was allowed to settle before use. The rainwater stored in the water tank still had low salinity and remained below irrigation water quality standards (EC 97.88 µS•cm^{-1}; pH 6.82), thereby potentially reducing the risk of pathogen presence and salt accumulation that could threaten plant growth. Furthermore, the slightly acidic pH of harvested rainwater makes it suitable as a nutrient solution in hydroponic systems, thereby supporting plant growth and yield.

The reduced supply of macronutrient composition in the RWH treatment still produced nutrient solution concentrations (2.17 dS•m^{-1}) that were not significantly different from the control (2.25 dS•m^{-1}), although they were slightly lower. These values were within the optimal range to ensure adequate nutrient supply and support optimal crop production (Domingues *et al.* 2012; Sharma *et al.* 2018). Conversa *et al.* (2021) reported that a higher lettuce weight was produced at an EC 2.5 dS•m^{-1} (97.9 g) compared to EC 3.5 dS•m^{-1} (92.9 g). This is consistent with Zhang *et al.* (2016) and Adhikari *et al.* (2019), who found that crop consumption and yield decline as nutrient solution EC increases from 3 dS•m^{-1}.

Furthermore, the SPAD index is an important indicator of chlorophyll concentration and nutritional status. Plants with higher SPAD values indicate adequate nutrient supply for photosynthesis, growth, and optimal yields (Hlavinka *et al.* 2013). The RWH treatment decreased the SPAD index by only 0.51% compared to the control, while nutrient solution consumption was relatively high. Macronutrient deficiency reduced nutrient uptake, as indicated by decreased nutrient solution consumption, yield, and SPAD index. Based on the total nutrient consumption in the RWH treatment of 1413 mL, the use of macronutrients was reduced by 3.45 mg N (2.30%), 0.04 mg P (0.21%), 2.09 mg K (1.39%), 6.23 mg Ca (8.31%), 9.61 mg S (24.02%), and 3.12 mg Mg (12.49%), respectively.

In addition, low-level macronutrient deficiency treatment (RWH treatment) produced leafy vegetable growth and yields of leafy vegetables that were not significantly different from the control. This indicates that the nutrients in harvested rainwater can adequately supplement deficiencies in the treatment level, supporting photosynthesis and biomass accumulation in hydroponic leafy vegetables (Lenni *et al.* 2020). Compared to lettuce, pak choi exhibited greater resilience and maintained yield under lower nutrient-deficiency conditions. Lettuce was more sensitive to macronutrient deficiency, particularly nitrogen, with a sharp reduction in fresh weight under the 75% and 50% treatments. This indicates that sufficient nitrogen is crucial for lettuce productivity, whereas pak choi can sustain yields despite nutrient reductions. The effect of treatments on plant growth observed after four weeks of growth showed different responses, as shown in Figure 6.

Fresh weight reduction in pak choi was more prominent in potassium deficiency, as indicated by a

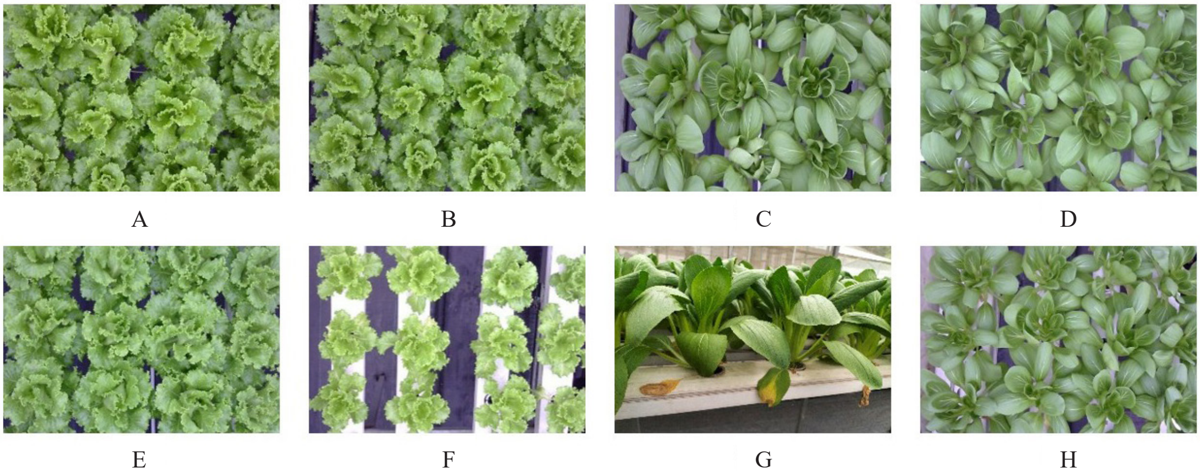

Figure 6. Visual impact of various nutrient treatments on the growth of pak choi and lettuce observed at week 4. (A) lettuce under control treatment, (B) lettuce under RWH treatment, (C) pak choi under control treatment, (D) pak choi under RWH treatment, (E) relatively high lettuce growth under K-75% treatment, (F) symptoms of nitrogen deficiency in lettuce (N-50% treatment) that significantly stunted growth, (G) symptoms of potassium deficiency in pak choi (K-50% treatment) indicated by the appearance of chlorosis on the lower leaves, (H) slightly stunted growth of pak choi due to nitrogen deficiency (N-50% treatment)

slight stunting and the appearance of marginal chlorosis on the lower foliage. Interestingly, reducing potassium does not significantly reduce lettuce's fresh weight and is relatively high compared to reducing nitrogen and phosphorus. Nitrogen deficiency more clearly caused stunting and reduced dry weight in lettuce, while phosphorus deficiency was indicated by dark, dull green coloration. Potassium deficiency caused leaf curl and marginal chlorosis on the lower foliage (Wiser and Blom 2016; Mu and Chen 2021; Veazie *et al.* 2022).

The implementation of rainwater harvesting systems for fertigation represents a viable and effective alternative for maintaining the yield of leafy vegetables. Utilization of elements present in rainwater as supplementary nutrients reduced macronutrient inputs by 0.21-24.02% compared to standard solutions, thereby enhancing economic efficiency and environmental friendliness. Therefore, farmers can implement rainfed fertigation in hydroponic enterprises to enhance fertilizer use efficiency and crop yields. Furthermore, evaluating variations of macronutrient concentrations provides hydroponic farmers with a reference to understand their implications for the growth and yield of leafy vegetables. Consequently, optimal macronutrient concentrations can be established to support crop productivity in the greenhouse.

Acknowledgements

This research was financially supported by the Center for Higher Education Funding and Assessment (Pusat Pelayanan Pembiayaan dan Asesmen Pendidikan Tinggi/PPAPT), Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, through the Indonesian Education Scholarship Program (BPI) in 2022.

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